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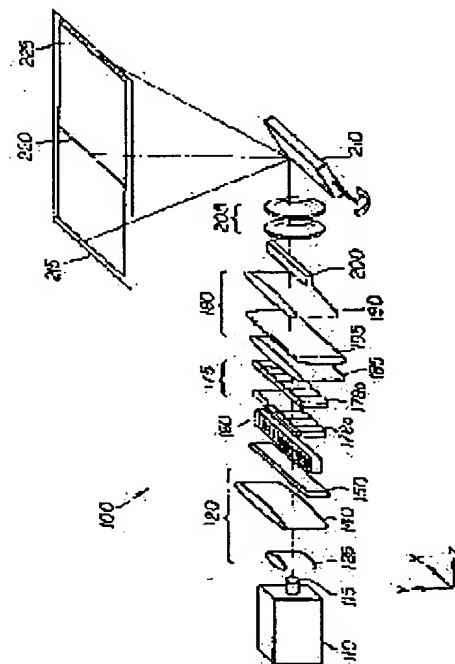
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(54) LASER PROJECTION DISPLAY SYSTEM

(57)Abstract:

PROBLEM TO BE SOLVED: To provide a laser display system by which speckles are reduced, coherence-induced artifacts in a spacial light modulator are removed and further while having a high throughput efficiency.

SOLUTION: A display apparatus includes a laser light source for emitting a light beam having a coherence length, a beam expander for expanding the light beam, the spacial light modulator and beam shaping optics for shaping the expanded laser beam to provide uniform illumination of the spacial light modulator. The beam shaping optics includes a fly's eye integrator having an array of plural lenslets, a diffuser located in the light beam between the laser light source and the beam shaping optics, an electrically controllable de-speckling modulator for modifying the temporal and spacial phase of the light beam and a projection lens for producing an image of the spacial light modulator on a distant screen.



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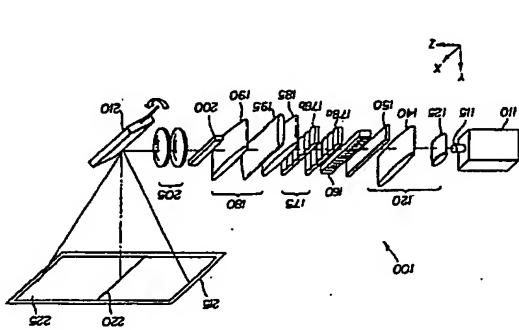
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(54) [発明の名称] レーザ投影ディスプレイシステム



(57) [要約]
【課題】 スペックルを低下させ、空間光変調器におけるコヒーレンスのアーチファクトを除去する一方で、高いスループット効率を有する、レーザディスプレイシステムを提供する。
【解決手段】 ディスプレイ装置は、コヒーレンスを有する光ビームを放射するレーザ光源と、上記光ビームを拡大するビーム拡大器と、空間光変調器と、上記拡大されたレーザビームを整形して上記空間光変調器の均一な照射を供給するビーム整形光学装置とを含む。上記ビーム整形光学装置は、複数のレンズレットにてなるアレイ光ビームにおいて上記レーザ光源と上記ビーム整形光学装置との間に配置されたディフューザと、上記光ビームの時間的及び空間的な位相を変化させる電気的に制御可能な空間光変調器と、遠隔のスクリーン上に上記空間光変調器の画像を生成する投影レンズとを含む。

(2) 特開2003-279889
10月27日に発行された特許文獻1と2001年5月15日に発行された特許文獻2においてフレイムライン (Flame Line) によって開示され、2001年5月15日に発行された特許文獻3においてネイベル (Nebel) によって開示されている。1998年4月14日に発行された特許文獻4においてモウルトン (Moulton) によって開示されたもう1つの例は、Q-ビーム (Q-beam) によって開示され、赤と緑と青の光を同時に発生するOPOシステムを備えた、QスイッチDPSSレーザー (Q-switched DPSS Laser) である。
【0004】空間光変調器は、レーザディスプレイシステムを可能にするもう1つの構成要素を提供する。2次元空間光変調器の例は、ジェネラティブ (JVO)、スリッパ (Three-five)、オーロラ (Aurora)、及びフィリップス (Phillips) から利用可能な液晶オシロン (LCO) 変調器のような反射型液晶変調器と、テキサス・インスツルメンツ (Texas Instrument) から利用可能なデジタル・ライト・プロセッシング (DLP) チップのようなマイクロミラー・アレイとである。1次元アレイとラスタースキャンされるシステムとに対する2次元変調器の利点は、必要な走査が存在しないことと、変調アレイにおける不均一性に起因する構造的アーチファクトが存在しないことと、フレームのリフレッシュレートよりも非常に高い周波数 (>120 Hz) でのレーザノイズに対する耐性にある。2次元空間光変調器の別の利点は、照射するビームの空間的コヒーレンスの低下に対する高い許容性にある。一方、いくつかの値ある変調器技術で、高いフィルファクタの1次元ディスプレイを容易に製造することができ、1次元又は2次元構成では非常に制限されている。1次元又は2次元の空間光変調器の例は、シリコン・ライト・マシ (Silicon Light Machines) によって製造され、1994年5月10日にブルーム (Bloom) 他に対して発行された特許文獻5に記述されたグレーティング・ラ イト・バルブ (GLV) と、2001年10月23日にコグネツ (Kogut) に対して発行された特許文獻6に記述された共振グレーティング変調器と、2000年7月4日にラマヌジャン (Ramanujan) 他に対して発行された特許文獻7に記述された電気光学反転グレーティング変調器を含む。
【0005】高いパワーの可視のレーザは、投影システム設計のために、拡張された光の範囲と簡便化された光学設計との可能性を含む新たな機会を提供するが、レーザ光は、他の点では、空間光変調器を備えた画像投影システムに用いるためには最適ではない。特に、レーザビームは、非常に小さな光学的な量 (optical volume) (エタレンデュ (etendue) 又はラグランジュ (lagrange)) 内で一般的にコヒーレントな光を放出する。非常に明るい光源である。エタレンデュは、焦点のスポットの面積と、焦点におけるビームの立体角との積である。ラグランジュ

これは、焦点のスポットの半径と開口数との積である。例えば、回折限界ビームを用いた単一モードの緑の波長のレーザーは約0.3 μmのラグランジュを有し、これに対してアークランプのような従来の白色光ランプの光源に対するラグランジュより約15000倍だけ小さい。そのような小さなラグランジュを備えたことによって、レーザは、極めて制御されたビームが望ましいフライニングスポットプリンタやレーザ光映写機のためのものを含む、ラスタ走査システムにおいて非常に効果的に使用可能である。

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(4) 特開2003-279889

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【0037】単一の装置部は、上部電極385と下部電極400との間の領域として定義されることが可能である。光線は、図3のx方向に沿って形成されているように、上部電極385と下部電極400との間を結晶層390に沿って伝播する。この領域を通過する光は、次式で定義される位相変化 $\Delta\phi$ を取得する。

[0038]

$$[\text{数}1] \Delta \phi = (\pi/\lambda) n^3 r_{33} |V/d|$$

【0039】教1で分かるように、位相変化 $\Delta\phi$ は、印加された電圧 V と、伝線の長さ l と、伝線の伝導度 σ と、光の波長 λ と、屈折率 n と、 Y カットのタンタル酸リチウム $Y:3\lambda$ 係数と関数である。5mmから50.0mmまでの伝線の長さ l と50.0 μm の厚さ t の基板のスペクトルにおける照射波長 λ のような妥当な製造パラメータトルにおける照射波長 λ と、0Vと16.0Vの間の動作電圧に對して、教2自身分の位相遷延を発生させることができる。当然のことながら、入力パラメータはすべて、与えられたチャネル幅 W は変調器部分に付いた多少の歪を生ずるように変更されることが可能である。遅延は、遅延波の伝導度は波数によって表わされてきた。これは、遅延を、媒体内での光の伝導度として除算された遅延時間によって与えられる時間遅延として機能することと等価である。

[0040] 再び図3を参照すると、複数の変調器部分335、336は、図4の断面図に示されたものと同様の構造を有する。上層335は、電圧調整部335aと、電圧調整部335aの下側に設けられた電圧調整部335bとを有する。電圧調整部335aは、電圧調整部335bよりも厚い。電圧調整部335bは、電圧調整部335aの下側に設けられ、電圧調整部335aの下部の両方を覆うように設けられる。電圧調整部335bは、電圧調整部335aの下側に設けられ、電圧調整部335aの下部の両方を覆うように設けられる。電圧調整部335bは、電圧調整部335aの下側に設けられ、電圧調整部335aの下部の両方を覆うように設けられる。

の場合がある。これにより、デバイスの片側の電圧に印
 加される変動電圧を用いた変調が可能となる。本スベッ
 クル除去変調器は、本デバイスが一連の変調器部分で構
 成され、上記変調器部分が、パターン化された電極構造
 体によってアプドレス指定され、かつ予め決められて印
 加される制御信号に個別に応答するか又は、電圧制御が可
 能である。各変調器部分は、異なる印加電圧、異なるア
 プドレス時間、又はこれらの組合せを用いて独立して操
 作して動作させることが可能である。電気的印加可能
 なスベックル除去変調器 16 のは、アナログ的印加可能
 される変調器、パルス幅変調されるデバイス、又はこれ
 らの組合せのいずれかとして使用可能である。スベッ
 クル除去変調器に印加される制御信号はまた、スベック
 ルの視認又はコントラストの底域をモニタするフィー
 ドバックループから導出され、次いでスベックルの大
 きさを維持するか又はさらに底域させるべく信号を駆動
 するように調整されることが可能である。x 方向に沿っ
 た任意の与えられた電極の間は、彼以下との幅から文字
 通りのミリの単位でのみ提供されておいてもよい。

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いるので、変調部と分間にクロストークを導入すること
は、さらなる相の変動を導入することによって、意図
された結果を促進することができ、設計者がクロスト
ークの効果を抑制することを希望する場合は、電極間
はクロストークを防止するの十分な間隔が必要とな
る。図3、図4及び図6に示されたもの以外にも、
本発明に於て有効とされる、かつレーザー投影ディスプレイ
100内で用いられ得る、電極的に制御可能なスベック
除空型変調器に於ける他の明示的な構造が存在する
ということは疑念を必要としない。

【0044】スベックルの発現は、検方向の位相プロファイルに対する空間的変動と、隣接領域間の時間的変動とによって決定される事が可能なので、電圧変動の制御可能なスベックル法装置の動作は、概念的に制御可能なように変更されることが出来る。前者の場合は、検方向の電圧の分布が電圧に対するアドレスの関数として設立される。この分布は、次に、検方向の位相の関数を画成する。時間的変動の場合には、異なる変数部分で同じ電圧のプロファイルを使用していることが出来る。しかしながら、時間において、相対的な発現は、隣接する領域が互いに位相相となないようになり、図 5 d に示されたように、両方の動作方法の組み合わせが最良の結果をもたらす。

【0045】電気的に制御可能なスペンゲル給注装置 160は、入射光の位相を歪曲する。又はスクランブルするように機能することができ、概念的には、図7a及び図7bにおいて、平行化された光線の場合についてこの効果が示され、平面上の平行な線面325が変換器160上へ垂直に入射するように向け付けられている。

の駆動電圧が印加され、図 7c に示されたとき、変調器 35 は変化する透過り率を有している。図 7a に示されたときには、変調器 160 は変化する透過り率を有している。図 7b に示されたとき、変調器 35 は変化する透過り率を有している。図 7c 及び 7d は、電気的に制御可能なスベックル除変調器 160 の光学システム内の集束する空間に配置された、同等の組合を示している。これらの面の透過率は特許されたものであって、単に一般的な概念を表すためのものであるというこは理解されなければならない。これらは必ずしも、1 だけ傾けられる必要はない。図 7d に示されたものは、1 だけ傾けられる必要はない。

[0046] 電気的に制御可能なスベックル除去装置180は、空間的な位置のずれを発生させることによって影響を及ぼすことができ、スベックルの項頭に設置する駆動部190が、それが使用されるシステムの設計にも依存する。本発明は特に、電気的に制御可能なスベックル除去装置部分にこの場合で、光軸のコヒーレンシー長より小さい速度 ($\Delta\phi < \lambda$) を提供する場面に適用している。矢印、距離、mmの数分の1が参考メートルまで(除/釐/厘の先)は

ラメラトリック発振型レーザーの場合は0.1乃至5.0 mm)の範囲にわたるコーレーレンス長を有する場合がある。タンタル酸リチウムに基いたスペクトル除去装置は数波長分の選別のみを提供する。従って、前述したように、このデバイスは、時間について変動する波面の歪み又は収差を発生させるために使用可能であるが、空間的又は時間的なコーレーレンスを目に見えように直後に変更するために使用可能ではない。幸いにも、時間的及び空間的に変化する位相は投写される画像内のスペクトルを変化させる、又は平均化するために使用可能であり、その変化が人の目の反応時間より速ければ、これによりスペクトルの知識や可能性が低減される。

【0047】一方で、電気的に制御可能なスペックル除去装置は、供給される照射源が光源のコヒーレンス長と同じオーダー（ $\Delta\phi \sim C$ ）であるシステムにおいても使用可能である。例えば、アークラザルのような典型的な白色光源はわずかに波長成分の程度のコヒーレンス長 C と極の光を放射するが、これは、タンタル酸リチウムに基づいたデバイスによる位相遅延に匹敵するものである。それに対応って、約1、0 mmの遅延を有する電気的に制御可能なスペックル除去装置は、小さなコヒーレンス長のレーザ（OPF強レーザ等）と組み合わせること、同じく基本的には遅延とコヒーレンス長を合わせることができる（ $\Delta\phi \sim C$ ）。このようにとを整合させることができる（ $\Delta\phi \sim C$ ）。このような場合では、電気的に制御可能なスペックル除去装置においては、空間的なコヒーレンスと時間的なコヒーレンスの両方を直接に変更するために、光学システム内で様々な方法で使用可能である。制御可能な位相遅延が光源からの光のコヒーレンス長を大幅に超過していれば（ $\Delta\phi \gg C$ ）、電気的に制御可能なスペックル除去装置160の使用によりさらに大きな効果を実現することができ、

【0048】スペックルの視認性を低減することにおいて、電気的に制御可能なスペックル除去変調器160の効力は、特定のデバイス（図3、図6a及び図6b）はこの種の例示的なデバイスを示している）の構造及びこの種のレーザー投影ディスプレイ100内でそれが使用される方法との両方に依存している。特に、電気的に制御可能なスペックル除去変調器160は、図1及び図2aに示されたようにフライイズ・アイ・インデグレート175の第1のレンズレットアレー178aに先行して配置される場合があり、図2bに示されたようにフライイズ・アイ・インデグレート175の内部に配置される場合もあり、もしくは同様にフライイズ・アイ・インデグレート175の第2のレンズレットアレー178bの後に配置される場合もある。1次元のデバイス（空同光変調器200）を照射するために使用される典型的なフライイズ・アイ・インデグレートに基づいた光学システムでは、各レンズレットアレー（178a及び178b）におけるレンズレットの個数（N）は比較的少なく、〜9乃至200

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子を使用可能であるということは理解される必要があり、レーザ投影システム100内のリニア空間光変調器200に先行するレンダリングのいくつかが球面レンズであって、かつレーザビーム及び交差アレイビームの両方を形成することが可能であるという点も理解される必要がある。同様に、投影レンズ205は、スクリーン215におけるアレイ方向又は交差アレイ方向のいずれかのスポット形成をさらに制御するために、円柱レンズ(図示せず)を含むことも可能である。同様に、電気的に制御可能なスベックル除去変調器を通る光の相互作用を最適化するように光ビームを予め調整するためには、交差アレイ光学装置(図示せず。)が、電気的に制御可能なスベックル除去変調器160に先行して設けられてもよいという点も理解される必要がある。この場合、交差アレイコンデンサ195又はその等価物は、電気的に制御可能なスベックル除去変調器160から放出される交差アレイ光ビームを、リニア空間光変調器200への入力として最適となるように適合化させる。また、フライズ・アイ・インテグレートに対して代替の二重均質化光学装置を使用可能であるという点も理解される必要がある。特に、(ムラン(Mu'llin)の特許)においてさらに記述されている、積分バー/カレイドスコープは、ビーム整形光学装置170のための代替の設計において使用可能であり、均一な照射を提供するとともに、ディフューザ150及び電気的に制御可能なスベックル除去変調器160と協働してスベックル低減に対して寄与する効果をもたらす。

[0057] 図8に、レーザ投影ディスプレイ100の代替構成が示され、ここでは、ビームスプリッタアレイ240を使用して、複合レーザビーム250のコヒーレンスを減少させるように光学距離調整を提供している。ビームスプリッタアレイ240は、レーザのコヒーレント長オーダーであるか又はこれより長い、隣接するビームスプリッタ245間の光学距離の長さ(Δd)を有する一連のビームレット245を生成する。(R)の部分反射率はミラーより成る装置を備えている。最後に、光学距離の差(Δd)は、レーザ110のコヒーレンス長C₁と同じオーダーのサイズである。ビームスプリッタアレイ240の複数のミラーは、最初のミラー(241a)から最後のミラー(241e)へと漸次増加する反射率によって、部分的に透過しかつ部分的に反射している。ビームスプリッタアレイ240は、複数のミラーのアレイとして示されているが、プリズムアレイ及び他の構造も使用可能である。ビームスプリッタアレイ240は、Rのビームレットを使用して複合レーザビーム250を生成する。ビーム拡大器として効果的に動作する。しかしながら、Rのビームレットはコヒーレンス長C₁に見合う異なる光学距離の長さ(Δd₁, Δd₂, Δd₃, など...)を進行するので、光の時間的なコヒーレンスは、複合レーザビーム250の空

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間的な広がりによって変化する。理想的には、R側のビームレット245のそれぞれは、他のものに関して時間的に非干渉性である。しかしながら、複数のビームレット245にわたるグループが互いにコヒーレントとなるように時間的なコヒーレンスの変化がもたらされることがあっても、レーザ110のコヒーレント光の状態が時間的に変動して、これらのグループは時間的にランダムに変化する傾向があるため、この方式は依然として有用である。

[0058] 典型的なレーザビーム115は、不均一な光の強度のプロファイル(図示せず)を有するので(ガウスプロファイルが一般的である。)、ビームレット245のそれぞれも不均一となり、同様に、複合レーザビーム250も不均一となる。図1のシステムの場合には、画像生成の必要条件下に合わせるように有効な光源のラランジュ又はエタンドーを最適化するために、ディフューザ150が挿入されている。ディフューザ150はまた、複合レーザビーム250をさらに幾分か均一にしかつコヒーレンスを低減させるように働く。同じく前述のように、空間光変調器200において照射の均一さを改善しかつスベックルの低減性を低下させるために、フライズ・アイ・インテグレート175が使用される。しかしながら、この場合は、第1のレンズレットアレイ178aが各ビームレット245にM個のレンズレットを照射させるように設計されているため、各ビームレット245は光バンプにおいて均一な照射に変換される。従って、各レンズレットアレイ178a及び178bには、少なくとも合計M×R個のレンズレットが存在する。スクリーン215における効果は、R側のレーザビームの各々が、ディフューザ、与えられたビームに使用されるM個のフライズ・アイ・レンズレットのペア、及びスクリーンによって決められる、その独自の微細なスベックルパターンを生成することである。M×R個のスベックルパターンは、電気的に制御可能なスベックル除去変調器160を使用しない場合、又はディフューザ150が動作しない場合でも、非干渉性の状態で加算されて全体の平均化を実現する。いくつかのほど重大でないアブレーションではこの程度のスベックルの低減で十分な場合があるが、重大なアブレーションに関する場合は、図8のレーザディスプレイシステム100は電気的に制御可能なスベックル除去変調器160を追加してさらに改善される。複合レーザビーム250内の時間的なコヒーレンスは既に重要な変数(implicitly variable)であるため、適用される位相の変化がコヒーレンス長より小さい(Δφ≪C₁)と仮定すれば、電気的に制御可能なスベックル除去変調器160を使用してビームレット245内の位相の波面を変化させることができる。先の議論の場合のように、電気的に制御可能なスベックル除去変調器160は、それがビーム整形光学装置170の共役面像平面のフーリエワールド(焦点深度(DOF)の)か

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外側)に存在するように、レーザディスプレイ100内に第1のレンズレットアレイ178aに先行して配置されることが可能である(図8を参照)。同様に前述のように、電気的に制御可能なスベックル除去変調器160は、共役像平面のフーリエワールドの下流側に、第2のレンズレットアレイ178bに近接して、図2bのようにならべて配置されるか、又は後に配置されるかのいずれかが可能である。それに代わって、電気的に制御可能なスベックル除去変調器160がコヒーレンス長に匹敵する位相の変化を提供すれば(Δφ≪C₁)、本変調器を使用してM個のレンズレットの各々における領域にわたって時間的及び空間的なコヒーレンスを最適化させることができる。ここで、これらの領域は、光の波長と比較して相対的に大きい(よって散乱も弱くない)。

[0059] これまでは、画像データを伝達するために、電気的に制御可能なスベックル除去変調器及び空間光変調器の両方を利用するレーザディスプレイシステムに係る本発明が、1次元の光変調器を使用することに關連して説明されてきた。電気的投影システムにおいて使用可能な、2次元(領域)の空間光変調器には広範な種類のものが存在するが、特に液晶光バンプ(LCD)及びマイクロカニカルミラーアレイ(デキヤス・インズツルメンツからのデジタル・ミラー・デバイスを含む)が卓越している。図1のレーザディスプレイシステムに關して、1次元の空間光変調器から2次元のタイプへ切り換えることによる主たる影響は、照射光装置と電気的に制御可能なスベックル除去変調器160との両方に2次元で動作するように変形させる必要があることにある。その場合、フライズ・アイ・インテグレート175は、典型的には、2次元パターンに展開されたフライズ・アイ・レンズレットのアレイ178(a, b)を使用し、ここで、上記レンズレットは波面を有している。同様に、ディフューザ150は、図1のリニアシステムでは好適な1次元の散乱ではなく、制御された2次元(又は領域)の散乱を提供する。このようなディフューザは、フジカール・オブティクス・コーポレーションからホログラフィック・ディフューザとして利用可能であり、又はコーニング・ロチェスター・フォトリニクス・コーポレーション(Corning-Rochester Photonics Corporation)からランダム化されたマイクロレンズアレイとして利用可能である。

[0060] 図3、図4、図6a及び図6bに詳細に示された空間的な電気的に制御可能なスベックル除去変調器160の様々な実施例は、1次元又はリニアのデバイスである。一連のこれらのデバイスを積み重ねる(スタックする)ことにより、もしくは一通のこれらのデバイスが光学システム内のオフセットした位置に配置することにより、2次元の電気的に制御可能なスベックル除去変調器を構成することが可能である。また、2次

元構成として使用するためにより導電性のある他の電気材料を使用し、次いで2次元の面像調整する空間光変調器のアレイを有するレーザディスプレイシステム内に配置されることが可能な、他のタイプの電気的に制御可能なスベックル除去変調器を設計可能であるという点も理解される必要がある。

[0061] 例えば図9は、LCDのような領域型の変調器アレイを使用するレーザ投影ディスプレイ100の断面図を示している。前述のように、レーザ110はレーザビーム115を放射し、レーザビーム115は、空間光変調器(液晶ディスプレイ255)を照射するため、ビーム拡大装置120とディフューザ150と、ビーム整形光学装置170とによって予め調整される。次いで、前述のように、ディフューザ150と、フライズ・アイ・インテグレート175と、電気的に制御可能なスベックル除去変調器160とはすべて、空間光変調器及びスクリーン215における2次元にわたる空間光変調器の存在を低減するために寄与する。図1のシステムとは異なり、図9のシステムでは、2次元のスクリーン上の画像は走査によって形成されるのではなく、投影レンズ205を使用することによって空間光変調器(液晶ディスプレイ255)をスクリーン215に直接に結像する。照射光は、プレラライザ260及び偏光ビームスプリッタ265を通過する。液晶ディスプレイ255は印加されるコマンド信号に従って、照射光を変調し、この光の偏光状態を画像に基づいて回転させる。投影レンズ205によってスクリーン215へと向けられる。変調された、画像を生成する光ビーム275は、偏光ビームスプリッタ265から反射される。偏光が回転され、光によって形成される。公称では、暗状態(dark state)を画成するために偏光アナライザ270が交差される向きで使用される。典型的なレーザ光源は偏光を放射するので、図9のレーザディスプレイ100では偏光がラライザ260を使用する必要のない場合がある。その場合は、レーザビーム115は、レーザ110によって放射されるときに十分に偏光されている(例えば100:1)。ディフューザ150も電気的に制御可能なスベックル除去変調器160も、本来この偏光コンストラクトの程度を有意に低下させないということが必要である。

[0062] 同様に、図10は、デキヤス・インズツルメンツから利用可能なDLPチップのようなマイクロカニカルミラーアレイ280を使用するレーザ投影ディスプレイの断面図を示している。光を変調するために、制御された偏光の効果を放する、液晶空間光変調器を用いたシステムとは異なり、マイクロカニカルミラーアレイ280は光のビームレットの角度的な制御を露光の基準で利用する。本システムは図1に示されたシステムと実質的に同じであるが、照射が、マイクロカニカルミラーアレイ280を超えて開口部290へと集束

する点が異なる。個別の画素は複数のマイクромリラーによって形成され、上記マイクромリラーは、光を、投影レンズ205の開口部290を通過させるように向けるか、又は停止部285（すなわちシュリーレン型光学システム）に向けるかのいずれかを行う。画素の明るさは、レンズの開口部290を介して光が向けられるフレーム内における時間の比率を選択することによって制御される。このタイプのシステムは、図10の場合のように、2次元の空間光変調器1レー、2Dのフライズ・アイ・システム、及び2Dの電気的に制御可能なスベックル除去変調器160を含むか、それによって1Dの空間光変調器1レー、1Dのフライズ・アイ・システム、0、及び図1で用いられているガルバノメータのようなスキヤナを含むかのいずれかで構成されることが可能である。

[0063] 簡単化のために、本発明は、単一のレーザと単一の空間光変調器とを使用して変態説明されているが、より一般的な議論がフルカラーのRGB投影ディスプレイに対して向けられる。システムは、別個の光学経路をたどって個々の赤と緑と青の空間光変調器を照射する。別個の赤と緑と青の光ビームは、別個の赤と緑と青の光ビームは、3つの別々のレーザによって生成される。変調された光ビームは、典型的には投影レンズの前に配置されたXプリズムによって結合された色となり、結果的に生じる光ビームがスクリーンに結像されて多色（polychromatic）画像を提示する。別個の赤と緑と青のビームは、3つの別々のレーザから、非線形光学装置の組み合わせを使用して3つのビームを出力する1つのOPO型レーザパッケージから、もしくは、後で色を分割される単一の白色光レーザビーム出力を供給するように統合されたOPO型レーザパッケージから発生されることが可能である。

[0064] 本発明の効用は、光学システムの照射部分内に配置された電気的に制御可能なスベックル除去変調器により、投影される画像においてスベックルが低減されるレーザディスプレイシステムを提供する。プロジェクタ内に統合された設計を使用してスベックルを除去するこの方法は、システムの動作性能が、劇場座にアプリケーション及び設計が変化する可能性のある、振動するスクリーンのような外部手段に依存しないということ意味する。それに加えて、このスベックル除去手段は、従来のスクリーンよりも低く行われているように画像生成光学装置内においては、照射システム内で機能するので、スベックルは、スクリーン上の画像品質に影響を与えないこと、さらには、知覚可能な境界よりも低下させることができる。さらに、照射システム内のスベックル除去変調器の設計及び動作を調整することにより、このシステムは、フィールドバックシステムを用いてオンザフライで最適化されるか、又はレーザ光源及び空間光変調器の技術が経時的に

進化するのに伴って段階的に最適化されるかのいずれかが可能である。最後に、このシステムは当然ながら、機械的かつ電気的に頑健であり、光効率が高く、アラインメント不良に対して敏感ではない。

[図面の簡単な説明]

[図1] 本発明に係る、電気的に制御可能な電気光学スベックル除去変調器とリニア空間光変調器とを有するレーザディスプレイシステムの斜視図である。

[図2a] 本発明に係る、電気的に制御可能な電気光学スベックル除去変調器とリニア空間光変調器とを有するレーザディスプレイの断面図である。

[図2b] 図2aに示されたレーザディスプレイ光学システムの一面に対する代替構成の断面図である。

[図3] 本発明に使用される、電気的に制御可能な電気光学スベックル除去変調器を実行する時間/位相遅延変調器の第1のパージョンの斜視図である。

[図4] 本発明に使用される時間/位相遅延変調器の第1のパージョンの断面図である。

[図5a] 視認性スベックルを提示する光学システム出力の位相プロファイルを示す図である。

[図5b] 低減された視認性スベックルを有する光学システム出力の位相プロファイルを示す図である。

[図5c] クロスプロットを提示する、電気的に制御可能なスベックル除去変調器の出力の位相プロファイルを示す図である。

[図5d] 地方方向及び時間について変化する位相振動の両方を有する電気的に制御可能なスベックル除去変調器の隣接する変調器部分間の相対的な位相遅延を示すチャートである。

[図6a] 本発明のレーザ投影ディスプレイにおいて使用可能な、代替の電気的に制御可能なスベックル除去変調器の斜視図である。

[図6b] 本発明のレーザ投影ディスプレイにおいて使用可能な、代替の電気的に制御可能なスベックル除去変調器の斜視図である。

[図7a] 本発明に係る変調器の効果を、入射する平行化された光線の場合に、影響を受けない波面に関して示す図である。

[図7b] 本発明に係る変調器の効果を、入射する平行化された光線の場合に、歪曲された波面に関して示す図である。

[図7c] 本発明に係る変調器の効果を、入射する集束する光線の場合に、影響を受けない波面に関して示す図である。

[図7d] 本発明に係る変調器の効果を、入射する集束する光線の場合に、アポートされた波面に関して示す図である。

[図8] コヒーレンス長のオーダーの複数の遅延を組み込んだ、本発明に係るレーザディスプレイシステムの代替の実施形態の断面図である。

[図9] 液晶ディスプレイ光バルブを使用する、本発明に係るレーザディスプレイシステムの断面図である。

[図10] マイクログラフ光バルブを使用する、本発明に係るレーザディスプレイシステムの代替の実施形態の断面図である。

[符号の説明]

100...レーザディスプレイシステム、

110...レーザ、

115...レーザビーム、

120...ビーム拡大光学装置、

125...発散レンズ、

130...発散ビーム、

140...コリメートレンズ、

145...平行化されたビーム、

150...ディフューザ、

160...電気的に制御可能なスベックル除去変調器、

175...フライズ・アイ・インテグレート、

178a...第1のレンズレットアレイ、

178b...第2のレンズレットアレイ、

180...ビーム整形光学装置、

185...コンデンサレンズ、

190...視野レンズ、

195...交差アレイ・コンデンサ、

200...リニア空間光変調器、

205...投影レンズ、

210...ガルバノメータミラー、

215...スクリーン、

220...終状態像、

225...傾斜画像、

240...ビームスプリッタレー、

241a乃至241e...ミラー、

245...ビームレット、

250...複合レーザビーム、

255...液晶ディスプレイ、

260...プレザラライザ、

265...偏光ビームスプリッタ、

270...偏光アナライザ、

275...変調された画像を生成する光ビーム、

280...マイクログラフミラーアレイ、

285...停止部、

290...開口部、

320...光、

325...波面、

330...歪曲された波面、

340...入力アセット、

345...出力アセット、

350、355、360...変調器部分、

370...バルク材料又は基板、

380...遅延領域、

385...上部電極、

390、392、395、397、399、420、4

25、430、435...電極、

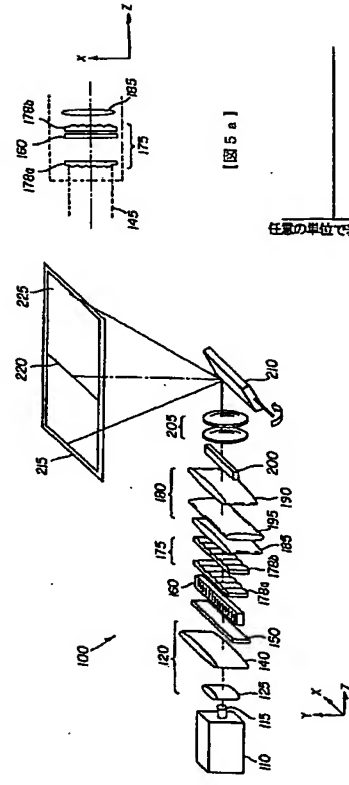
400...下部電極、

405...バンプ層、

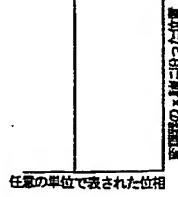
410...保護膜、

[図1]

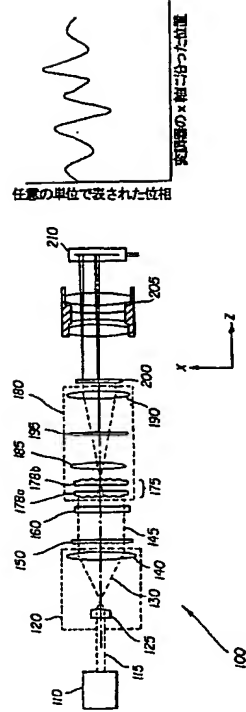
[図2b]



[図5a]



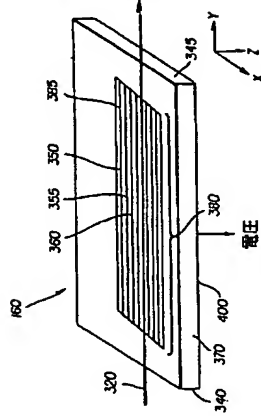
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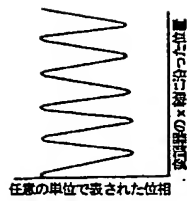
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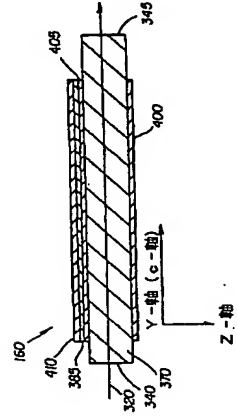
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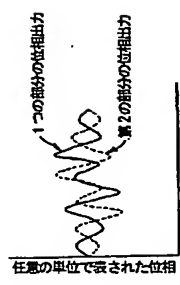
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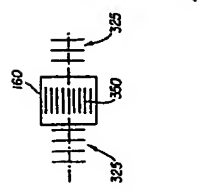
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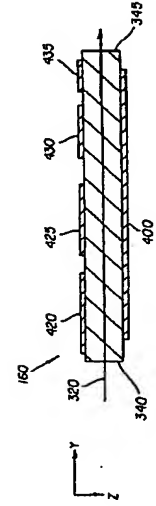
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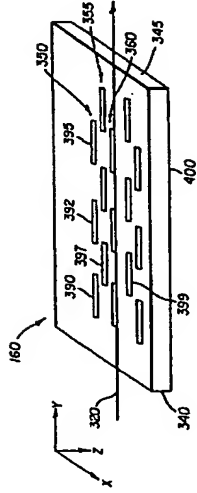
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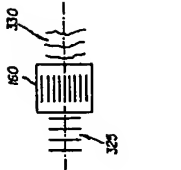
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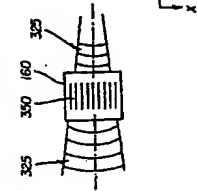
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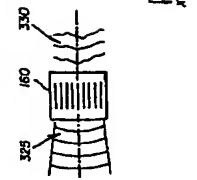
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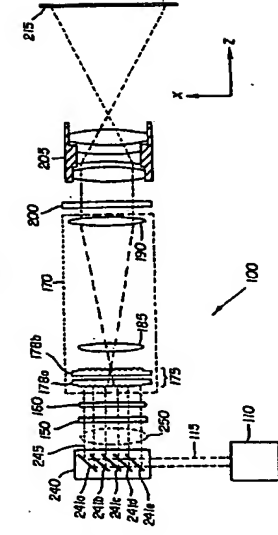
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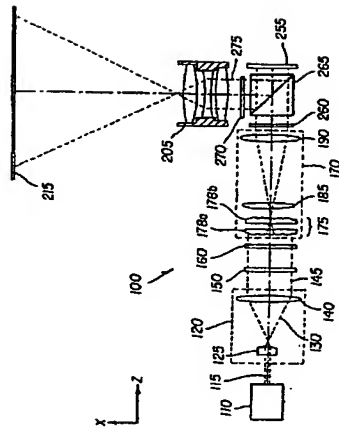
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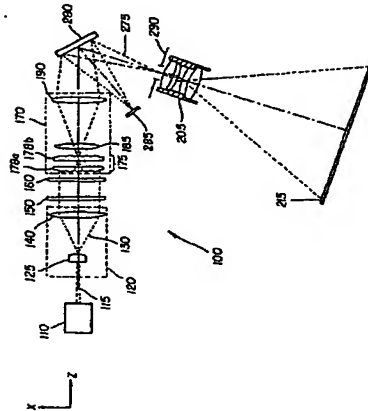
【図8】



【図 9】



【図 10】



フロントページの続き

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BC26 BC51

【外国語明細書】

- 1 -

LASER PROJECTION DISPLAY SYSTEMFIELD OF THE INVENTION

The invention relates to projection display apparatus employing a laser as a light source. More particularly, the invention relates to laser projection display apparatus having means for reducing the appearance of coherence-induced artifacts and speckle in the display.

BACKGROUND OF THE INVENTION

Projection display systems for the display of video images are well-known in the prior art. These systems can take the form of a white light source, most notably a xenon arc lamp, illuminating one or more light valves or spatial light modulators with appropriate color filtering to form the desired image, the image being projected onto a viewing screen.

Lasers have been known to be attractive alternative light sources to arc lamps for projection displays. One potential advantage is a wider color gamut featuring very saturated colors. Laser illumination offers the potential for simple, low-cost efficient optical systems, providing improved efficiency and higher contrast when paired with some spatial light modulators. One disadvantage of lasers for projection display has been the historical lack of a cost-effective laser source with sufficient power at visible wavelengths. However, such lasers (albeit, still high cost) are now produced by JenOptik and Lumera Laser, GmbH, and are mode-locked, diode-pumped, solid-state lasers, each with a nonlinear-optical system featuring an optical parametric oscillator (OPO) to simultaneously generate red, green, and blue light. This system has been disclosed by

Wallenstein in US Patents 5,828,424, issued October 27, 1998, and 6,233,025 issued May 15, 2001; and by Nebel in US Patent 6,233,089, issued May 15, 2001. Another example disclosed by Moulton in US Patent 5,740,190, issued April 14, 1998 is developed by Q-Peak and is a Q-switched DPSS laser with an OPO system to simultaneously generate red, green, and blue light.

Spatial light modulators provide another component that enables laser display systems. Examples of two-dimensional spatial light modulators are

reflective liquid crystal modulators such as the liquid-crystal-on-silicon (LCOS) modulators available from JVC, Three-Five, Aurora, and Philips, and micromirror arrays such as the Digital Light Processing (DLP) chips available from Texas Instruments. Advantages of two-dimensional modulators over one-dimensional array modulators and raster-scanned systems are the absence of scanning required, absence of streak artifacts due to non-uniformities in the modulator array, and immunity to laser noise at frequencies much greater than the frame refresh rate (> 120 Hz). A further advantage of two-dimensional spatial light modulators is the wide tolerance for reduction of the spatial coherence of the illuminating beam. On the other hand, some valuable modulator technologies can be readily fabricated as high fill factor one dimensional devices, although the two dimensional constructions are more limited. Examples of one-dimensional or linear spatial light modulators include the Grating Light Valve (GLV) produced by Silicon Light Machines and described in US Patent 5,311,360 issued May 10, 1994 to Bloom et al.; the conformational grating modulator, described in US Patent 6,307,663 issued October 23, 2001 to Kowarz; and the electro-optic reflective grating modulator described in US Patent 6,084,626 issued July 4, 2000 to Ramanujan et al.

Although high power visible lasers offer new opportunities for the design of projection systems, including the possibilities of expanded color gamut and simplified optical designs, laser light is in other ways not optimum for use in image projection systems with spatial light modulators. In particular, lasers are very bright sources, which emit generally coherent light within a very small optical volume (etendue or lagrange). Etendue is the product of the focal spot area and the solid angle of the beam at the focus. Lagrange is the product of the focal spot radius and the numerical aperture. For example, a single mode green wavelength laser with a diffraction-limited beam has a lagrange of about $0.3 \mu\text{m}^2$, which is about 15,000 times smaller than the lagrange for a conventional white light lamp source, such as an arc lamp. With such a small lagrange, lasers can be used very effectively in raster scanning systems, including those for flying spot printers and laser light shows, where a tightly controlled beam is desirable.

On the other hand, in an image projection system, in which an image-bearing medium such as a film or a spatial light modulator is imaged to a screen or a target plane, the high coherence and small lagrange of the laser is ultimately undesirable. In such an imaging system, the lagrange is determined by the linear size of the projected area (size of the spatial light modulator) multiplied by the numerical aperture of the collection lens. The related quantity, etendue, is calculated similarly. In many white light projection systems, the projection lens is quite fast ($f/3$ for example) to collect as much light as possible. Even so, the typical white light lamp source overfills both the light valve and the projection lens, and significant light is lost. For example, in a representative system using a common $0.9''$ diagonal light valve and an $f/3$ projection lens, the optimum light source would have approximately a 2.0-mm lagrange to provide proper filling without overfill. However, a standard white light lamp, with a typical lagrange of 2-10 mm, is not sufficiently bright and will generally overfill this representative system.

In the case of a laser display system using image area projection (as opposed to raster scanning), the opposite problem arises, the lasers being too bright. Furthermore, it is not desirable to illuminate the spatial light modulator with a coherent source, because of the potential for interference effects, such as fringes, which may overlay the displayed image. Diffraction artifacts can arise from illuminating the grid electrode pattern of a liquid crystal panel, an X-cube with a center discontinuity, or any dust or imperfections on the optical elements with a highly coherent beam of light. Therefore, a reduction of the source brightness (or an increase in the source lagrange) is a necessity for such laser projection systems.

A defined reduction of the source brightness can also provide an important opportunity. The projection display optical system can be designed to optimize and balance the system requirements for resolution, system light efficiency, and system simplicity. By defining the system f-number on the basis of a criterion other than system light efficiency, the specifications on other system components such as the projection lens, color filters, and polarization optics can

be eased, dramatically reducing system costs compared to some lamp-based projection systems.

While laser sources can be optimized for use in projection display illumination and imaging systems, there is the consequent major disadvantage of speckle to be dealt with. Speckle arises due to the high degree of coherence (both spatial and temporal) inherent in most laser sources. Speckle produces a noise component in the image that appears as a granular structure, which both degrades the actual sharpness of the image and annoys the viewer. As such, the speckle problem, as well as the historical lack of appropriate laser sources, has inhibited the development of marketable laser-based display systems.

The prior art is rich in ways of attempting to reduce speckle. One common approach is to reduce the temporal coherence by broadening the linewidth of the laser light. Other approaches to reducing the temporal coherence are to split the illuminating wavefront into beamlets and delay them relative to each other by longer than the coherence time of the laser, see for example US Patent 5,224,200, issued June 29, 1993 to Rasmussen et al. Dynamically varying the speckle pattern by vibrating or dynamically altering the screen is another way of reducing the visibility of the speckle pattern; see, for example, US Patent 5,272,473 issued December 21, 1993 to Thompson et al. Another speckle reduction approach involves coupling the laser light into a multimode optical fiber and vibrating the fiber to cause mode-scrambling as described in US Patent 3,588,217, issued June 28, 1971 to Mathisen.

Another family of de-speckling solutions uses a diffusing element that is moved or vibrated within the projector system. Typically, this is done at an intermediate image plane, as disclosed in US Patent 4,035,068, issued July 12, 1977 to Rawson. One disadvantage of this approach is that the diffusion must occur precisely at the image plane or a softening of the image will occur. Also, the projection lens is complicated by the requirement to provide an intermediate image plane. A means of dynamically varying the speckle pattern by dynamically diffusing the laser beam in the illumination path of the device would be preferable. A hologram illumination system utilizing this approach has been

disclosed by vanLigten in US Patent 3,490,827, issued January 20, 1970, in which a diffuser is rotated in the focus of a beam expander. Florence discloses in US Patent 5,313,479, issued May 17, 1994, illuminating a light valve through a rotating diffuser. These approaches have the disadvantage of not being adaptable to uniform efficient illumination of a rectangular spatial light modulator.

Butterworth et al. in US Patent 6,005,722, issued December 21, 1999, disclose a system in which a variable-thickness plate is rotated in the illumination of a light-pipe homogenizer. When used with lasers, though, light pipe homogenizers require either a large numerical aperture or a substantial length to achieve sufficient uniformity, and offer less control with fewer degrees of design freedom than systems designed with fly's eye optics. Therefore, it is harder to control the illumination brightness while producing a uniform illumination in a compact system.

Finally, the laser projection system disclosed by Trismadi in US Patent 6,223,984, issued November 27, 2001, describes a design in which a wavefront phase modulator is used to impart a structured phase profile across the imaging beam. Image data is imparted to the beam by means of a linear GLV type spatial light modulator. This modulator is imaged to an intermediate plane where the wavefront modulator resides, and the intermediate image is

subsequently re-imaged to a screen, with the image scanned out through the motion of a galvanometer. This system relies on the fact that a static phase profile, which is provided by the wavefront modulator, is imparted to the line image in the narrow (in-scan) direction. At any instant of time, a single point on the screen will be illuminated by one point on the phase profile. The total intensity at a single point on the screen is the "incoherent" addition of all the phases. Further the phase profile of the wavefront modulator must be such that the interference effects from the high and low phase steps generally cancel each other out. While the system of the '984 patent does provide some speckle reduction, the fact that wavefront modulator is located at an intermediate image plane within the imaging system, rather than within the illumination system, compromises the system performance, as the phase changes are limited by the

constraint of not significantly effecting image quality. Also, as the

aforementioned wavefront modulator is a static device, which is constructed as a passive spatially variant phase grating, it provides less control and variation of phase than an active device, and therefore potentially less speckle reduction.

Another disadvantage of using a laser as a light source in an image projector is the susceptibility of interference or the occurrence of diffraction artifacts in the light valve. This is especially true of liquid crystal modulators, wherein the thin-film structure can result in fringes in the image due to non-uniformities in the film layers. Diffraction artifacts arise from illuminating a grid electrode pattern in the light modulator with a highly coherent beam of light.

There is a need therefore for a laser-based display system that uses a spatial light modulator, allows control of the illumination brightness to optimize system design, and exhibits reduced speckle and eliminates coherence artifacts at the spatial light modulator while exhibiting high throughput efficiency.

SUMMARY OF THE INVENTION

The need is met according to the present invention by providing a display apparatus that includes a laser light source for emitting a light beam having a coherence length, a beam expander for expanding the light beam, a spatial light modulator, beam shaping optics for shaping the expanded laser beam to provide uniform illumination of the spatial light modulator, the beam shaping optics including a fly's eye integrator having an array of lenses; a diffuser located in the light beam between the laser light source and the beam shaping optics; an electrically controllable de-speckling modulator for modifying the temporal and spatial phase of the light beam; and a projection lens for producing an image of the spatial light modulator on a distant screen.

ADVANTAGES

The present invention provides for a laser display system in which speckle is reduced in the projected image by means of an electrically controllable de-speckle modulator positioned within the illumination portion of the optical system. This method of de-speckling, using an integrated design within the projector, means that the operational performance of the system does not depend

on external means, such as the vibrating screens, which may vary in application and design from one theatre to another. Additionally, as this de-speckling means functions within the illumination system, rather than within the imaging optics, as is more conventionally done, speckle can be reduced to below perceptible limits without impacting the on screen image quality. Furthermore, by tuning the design and operation of the de-speckle modulator within the illumination system, this system could be optimized either on-the-fly with a feedback system, or progressively, as the laser source and spatial light modulator technologies evolve over time. Finally, this system should be mechanically and electrically robust, light efficient, and insensitive to mis-alignment.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a perspective view of the laser display system with an electrically controllable electro-optic de-speckling modulator and a linear spatial light modulator according to the present invention;

Fig. 2a is a cross-sectional view of the laser display with an electrically controlled electro-optic de-speckling modulator and a linear spatial light modulator according to the present invention;

Fig. 2b is a cross-sectional view of an alternate configuration for a portion of the laser display optical system depicted in Fig. 2a;

Fig. 3 is a perspective view of a first version of the electrically controllable electro-optic de-speckling time/phase delay modulator used in the present invention;

Fig. 4 is a cross-sectional view of the first version of the time/phase delay modulator used in the present invention;

Fig. 5a is a representation of the phase profile of the output of an optical system exhibiting visibility speckle;

Fig. 5b is a representation of the phase profile of the output of an optical system that has reduced visibility speckle;

Fig. 5c is a representation of the phase profile of the output of an electrically controllable de-speckling modulator exhibiting cross talk;

Fig. 5d is a chart of the relative phase delay between adjacent modulator sites for an electrically controllable de-speckling modulator with both lateral and time varying phase perturbations;

Figs. 6a and 6b are perspective views of alternate electrically controllable de-speckling modulators that can be used in the laser projection display of the present invention;

Figs. 7a and 7b illustrate the effect of a modulator of the present invention in terms of an unaffected wavefront and an distorted wavefront respectively, in the case of incident collimated light;

Figs. 7c and 7d illustrate the effect of a modulator of the present invention in terms of an unaffected wavefront and an aborted wavefront respectively, in the case of incident convergent light;

Fig. 8 is a cross-sectional view of an alternative embodiment of the laser display system according to the present invention, incorporating multiple delays on the order of the coherence length;

Fig. 9 is a cross-sectional view of the laser display system according to the present invention using a liquid crystal display light valve; and

Fig. 10 is a cross-sectional view of an alternative embodiment of the laser display system according to the present invention using a micromirror-array light valve.

DETAILED DESCRIPTION OF THE INVENTION

Laser display system 100 according to one embodiment of the present invention, is shown in perspective view in Fig. 1, and includes a laser 110 that emits a laser beam 115 of a desired wavelength in either a continuous or pulsed fashion. The laser 110 can be, for example, a solid state laser, a fiber laser, a gas laser, or a semiconductor laser. Laser 110 is preferably a diode-laser-pumped solid state laser including a laser crystal (e.g. Nd:YAG, Nd:YLF, Nd:YVO₄, or Yb:YAG) that emits infrared pulses of light and includes nonlinear optics (typically optical parametric oscillators (OPOs)) that convert the infrared pulses of light from the laser crystal into red, green, and blue pulses of light. Mode-locked RGB lasers suitable for laser 110 are manufactured by Lumera

Laser GmbH and JenOptik. Another suitable laser is the Q-switched RGB laser developed by Q-Peak. For simplicity, the laser display system 100 is depicted for one wavelength only. These lasers generally produce high quality single mode beams, which have moderate laser line widths (<1.5 nm), small source inhomogeneities (<0.5 μ m), and moderately long coherence lengths C_L (0.1-10.0 mm).

Laser display system 100 is shown in cross-sectional view in Fig. 2a, to clarify some aspects of the design not readily shown in the perspective view of Fig. 1.

Beam expansion optics 120 expand the laser beam to produce a collimated beam 145 with the necessary diameter to nominally fill the aperture of beam-shaping optics 170. The beam expansion optics 120 can be, for example, an afocal pair of lenses, as is well-known to one skilled in the art of optics.

Alternatively, for example, a three element zooming Galilean or Keplerian beam expander could be used. The afocal pair beam expansion optics 120 comprises a diverging lens 125 and a collimating lens 140. The diverging lens 125 can be a single lens or a compound lens such as a microscope objective, and transforms the light beam 115 into a diverging beam 130. The collimating lens 140 can be a single or a compound lens, and transforms the diverging beam 130 into a collimated beam 145. This collimated beam 145 interacts with diffuser 150 and an electrically controllable de-speckling modulator 160, and then is further altered by beam shaping optics 170.

As the laser display system of Figs. 1 and 2a uses a linear spatial light modulator 200, which is long in the x direction, and narrow in the y-direction, the beam expansion optics 120 and beam shaping optics 170 are constructed anamorphically, and generally use an appropriate arrangement of cylindrical lenses. In particular, it is typically desirable to flood illuminate linear spatial light modulator 200 with a long narrow line of uniform telecentrically incident light. For example, the illuminating light beam may have a uniform light profile extending 25-75 mm in the array (x) direction), whereas, the narrow cross array direction light only illuminates a 20-100 μ m width, typically with either a uniform or Gaussian beam profile. In the simplified case of the laser display system of Fig. 1, the cross array optics, which condense or focus the beam of light

onto linear spatial light modulator 200 are shown for simplicity as a single lens, cross array condenser 195.

Thus, in the case of the Fig. 1 system, for a laser projection display using a linear spatial light modulator 200, the beam expansion optics 120 work in the array direction only, and are thus anamorphic, providing beam expansion in the direction of the linear light valve (x-direction). In this case the beam-shaping optics 180 are also anamorphic (cylindrical cross-sections), with optical power in the x-direction, and flat surfaces in the y-direction (except for cross array condenser 195). Beam shaping optics 180 includes a fly's eye integrator 175.

The fly's eye integrator 175 provides efficient, uniform illumination over the area of a linear spatial light modulator 200. The fly's eye integrator 175 includes a first lenslet array 178a and a second lenslet array 178b, which are typically identical. The first and second lenslet arrays 178a and 178b include a plurality of lenslets with cylindrical surfaces, arrayed in a one-dimensional pattern. The second lenslet array 178b is separated from the first lenslet array 178a by approximately the focal length of the lenslets on the first lenslet array 178a, such that each lenslet in the first lenslet array 178a focuses light into the corresponding lenslet in the second lenslet array 178b. Other designs are possible in which the first and second lenslet arrays 178a and 178b are different, but are matched to provide the desired illumination.

Alternately, the first and second lenslet arrays 178a and 178b can be integrated in a single block of glass or plastic. Also, the invention can be accomplished without the use of the second lenslet array 178b, especially if a small diffusion angle is used.

The beam-shaping optics 180 also includes a condenser lens 185 and a field lens 190 located behind the fly's eye integrator 175. The second lenslet array 178b, works in combination with the condenser lens 185, to image the lenslets of first lenslet array 178a in overlapping fashion to provide an area of uniform illumination at the linear spatial light modulator 200. Field lens 190 provides telecentric illumination of the linear spatial light modulator 200 in order to desensitize the system to defocus errors and to minimize the total numerical

aperture of the illumination. Field lens 190 nominally has a focal length equal to the lenslet focal length multiplied by the magnification of the illumination image.

The spacing between the field lens 190 and the condenser lens 185 should likewise be generally equal to the focal length of the condenser lens 185 in order to make the illumination telecentric. The focal lengths of the lenslet arrays and condenser lens 185 are typically chosen to provide sufficient working distance near the linear spatial light modulator 200 that the opto-mechanics can be designed with relative ease. While individual lenslets may be as small as 100 μm in width, or as large as ~ 8 mm in width, the individual lenslets are typically 1-5 mm wide. The range of available lenslet sizes does depend on the manufacturing technologies used.

The linear spatial light modulator 200 generates a single line 220 of the image at any moment in time. A scanner such as a galvanometer mirror 210, a spinning polygon, or a rotating prism sweeps the image lines across the screen to form a two-dimensional area image 225 on the screen 215. In the case of the laser display system 100 depicted in Figs. 1 and 2a, the system is configured as a post-objective scanner, with projection lens 245 located prior to galvanometer mirror 210. As an example, if linear spatial light modulator 200 has an active area 40 mm long, and the desired image size on screen 215 is 30 ft. wide, then projection lens 205 would operate with a magnification of $\sim 230\times$.

A variety of different technologies can be used for linear spatial light modulator 200. As simplistically depicted in Figs. 1 and 2a, this device is a transmissive modulator, which encodes the image data in the light beam by modulating the light in some way. This device, for example, could be an electro-optic modulator array made from PLZT which rotates the polarization of the incident light on a per pixel basis. In that case, a polarization beam splitting prism (not shown) would be located somewhere between linear spatial light modulator 200 and galvanometer mirror 210, so as to separate the modulated and unmodulated portions of the light beam. Alternately, the linear spatial light modulator 200 could be a transmissive acousto-optical array device, much like the device in discussed in US Patent 5,209,178, issued May 3, 1994 to Gross which

imparts a phase profile to the incident beam on a per pixel basis. In that case, a Schlieren type optical system can be constructed by placing a spatial filter (not shown) at Fourier plane internal to projection lens 205. Reflective grating modulator arrays can also be used, such as grating light valve (GLV) described in US Patent 5,311,360, issued May 10, 1994 to Bloom et al.; a conformal grating device as described in US Patent 6,307,663, issued October 23, 2001 to Kowarz; or an electro-optic grating as described in US 6,084,626, issued July 4, 2000 to Ramasujan et al. In these cases, the laser projection display 100 must also be modified to deflect the light beam down onto the modulator and return the reflected beam into the system (such modifications are not shown in Figs. 1 & 2a but are within the ordinary skill in the art of optical systems design).

A diffuser 150, is disposed between the laser 110 and the beam-shaping optics 180, to modify the brightness or etendue of the laser light to match the imaging requirements of the projection system. In the case of the laser display system 100 of Figs. 1 and 2a, which has a linear spatial light modulator 200, diffuser 150 nominally is also one-dimensional. That is, diffuser 150 only diffuses light along the length of the light valve array (x direction in the figure), while leaving the beam nominally unaltered in the y-direction. The one-dimensional diffuser 150 produces just enough diffusion in order to efficiently illuminate the light valve and not enough to introduce flare light at the image. Exemplary one dimensional diffusers include diffractive line generators, available from MEMS Optical, and elliptical holographic diffusers, available from Physical Optics Corp.

In particular, diffuser 150 is employed within the illumination optical system of the laser projection display 100 in order to reduce the source brightness (increasing lagrange). The diffuser angle θ_D and the location of the diffuser 150 are selected accordingly. The lagrange of the system will be dominated by the product of the illumination beam profile half-width on the diffuser 150 and the half-angle of the light scattered by the diffuser 150. The desired system lagrange may be inferred from the specified image resolution, which in turn depends on the resolution of the linear spatial light modulator 200

and the imaging properties of the projection lens 205. By comparison, in the typical lamp based projector, the system lagrange will be determined by the need to maximize system light efficiency. As a result, the projection lens for the laser display may have an f-number in the f7 to f15 range instead of the f3 required by the prior art lamp based systems. The actual design target for the lens f-number will depend on the imaging criteria specified to determine the quality of the lens (for example, a Rayleigh or Sparrow imaging criteria could be applied).

As an example, the combination of a 40 mm long linear spatial light modulator 200 and an f10 projection lens 205, will specify a target lagrange of the projection system of ~1.0 mm in the X-direction. In this example, the diffuser 150 can have a half angle $\theta_D = 5.0^\circ$ and be placed within the illumination system such that it is illuminated by a collimated beam with 22-mm diameter. In this example, the lagrange of the laser light will be reduced from ~0.3 μm to ~1.0 mm, and a specular f10 beam could be provided to spatial light modulator 200, assuming the intervening optical system has the proper magnification and lens structure. Thus, through the selection of the appropriate diffuser 150, the lagrange or brightness of the effective laser light source can be defined to match the needs of the optical system, thereby boosting system light efficiency and simplifying the optical design, as compared to a traditional lamp based system.

While diffuser 150 does reduce the coherence of the laser light to some extent, the laser light will remain sufficiently coherent to impart speckle into the outgoing beam. Unless this speckle is further reduced, it will be present at both the linear spatial light modulator 200 and the screen 215 as an undesired random variation in light intensity. However, the fly's eye integrator 175, which primarily provides uniform illumination to the linear spatial light modulator 200, also amplifies the effect of the diffuser 150 on de-speckling and artifact removal. This comes about by overlapping many contributions from the diffuser 150 on the linear spatial light modulator 200 and therefore in the image on the screen 215. Although the resulting speckle within the illuminating light at the linear spatial light modulator 200 and screen 215 is significantly reduced in size and magnitude compared to a similar system without the fly's eye integrator 175, this remaining

speckle can still be objectionable in critical applications. A projection display, which combines a very high to screen magnification, a high gain screen, and observers viewing the screen near the human visual acuity limits, is such a critical application.

5 A primary purpose of the present invention is to provide a laser projection display that employs a combination of internal means to de-speckle the output of a pixilated optical system. Speckle in such a system can be reduced when adjacent pixels or groups of pixels are not perfectly in phase with one another either spatially or temporally. A locally uniform phase profile, which extends across a group of pixels, and which can exhibit speckle is shown in Fig. 5a. The present invention uses means (including electrically controllable de-speckle modulator 160) to alter the phase profile shown in Fig. 5a across an extent of the light beam such that it more closely resembles the profile shown in Fig. 5b. Fig. 5b shows a more random phase profile in which at any given instant in time 10 adjacent regions along the x-direction see different phase profiles. Also effective, would be a geometry that provides a periodic or quasi-periodic profile as shown in Fig. 5c, which can for example originate with crosstalk between adjacent modulator sites. While periodic or quasi-periodic phase profiles reduce speckle, other undesired artifacts may be introduced by such periodic phase structures. For that reason, the preferred mode of operation according to the present invention is one creating a phase profile as seen in Fig. 5b. In a preferred embodiment of the present invention, the laser projection display 100 includes an electrically 15 controllable electro-optic de-speckling modulator 160, having a series of modulator sites that receive control signals to provide localized random phase changes to the incident light, thereby helping to reduce speckle visibility in the images displayed by the system. It should be noted that there need not be a one to one correspondence between the pixels of the spatial light modulator in the optical system and the modulator sites of the electrically controllable de-speckling modulator 160. In fact the optical system need not be pixilated at all, and for 20 example could use an analog medium such as film for the image modulation..

The electrically controllable de-speckling modulator 160 used in the laser display 100 of the present invention provides enough variation of phase within the light beam that the viewer or viewing system receives a reduced speckle image when the modulator is used in conjunction with an appropriate optical system. By independently electrically addressing the modulator sites, each 5 site in the electrically controllable de-speckling modulator 160 can introduce phase delays in the light beam with respect to the neighboring sites. A different voltage or voltage duration is applied to each site (or group of sites), thus producing a phase delay corresponding to as much as several waves of propagation in the light. This variation to the phase profile significantly reduces the appearance of speckle. By picking a voltage distribution that spatially provides a perturbed phase front and varying it in time, both spatial and temporal phase variation is introduced into the light beam.

The electrically controllable de-speckling modulator 160 is included in the optical system of the laser projection display in such a manner that its' controllable spatially varying random phase profiles translate into a reduction of speckle. The electrically controllable de-speckling modulator 160 reduces speckle through a reduction of coherence, or a randomization of phase in a light beam spatially and/or temporally. The inclusion of the electrically controllable de-speckling modulator 160 in the optical system serves to effectively scramble the phase profile of a light beam by varying the refractive index profile in the medium through which light travels.

Referring to Fig. 3, there is shown a first example of an electrically controllable de-speckling modulator 160 of a type that could be used in the laser projection display of the present invention. The electrically controllable de-speckling modulator 160 is a patterned device including a collection of addressable modulator sites that produce controlled time or phase delays with respect to adjacent pixels in accordance with signals, or data provided to individual modulator sites. Commonly-assigned co-pending USSN 09/924,619, filed August 8, 2001, by Ramanujan et al, describes the design and operation of de-speckling modulators in greater detail than provided here.

The electrically controllable de-speckling modulator 160 comprises a bulk electro-optic substrate 370 with a series of individual modulator sites 350, 355, 360, etc. Each modulator site 350 has a delay region 380 through which a beam of light 320 encounters a time or phase delay in relation to the electric field applied between top electrode 385 and bottom electrode 400. Beam of light 320 enters bulk electro-optic substrate 370 through an input facet 340, after which it traverses the modulator, and exits through output facet 345.

The choices of electro optic materials from which to build the electrically controllable de-speckling modulator are numerous and include Lithium niobate, lithium tantalate and PLZT. For the sake of simplicity, further discussion of the parameters for the electrically controllable de-speckling modulator will center around the use of lithium tantalate illuminated at 633 nm, but it should be understood the geometry is applicable to a variety of materials and illumination wavelengths. If a different material is employed, care must be taken to ensure the correct axes are employed. For example, use of PLZT in such a device design can produce orders of magnitude greater phase delay along a modulator site due to the larger electro-optic coefficient. However, the crystal must be oriented in a manner such that the applied electric field interacts with the optical field through the appropriate axes of the crystal.

In the case of lithium tantalate, the geometry represented here is shown as y-cut, meaning that light propagates along the y-direction and electric field is applied along the z-direction. For best results, the light traveling through the modulator is polarized along the x-direction (transverse direction). For the purposes of the electrically controllable de-speckling modulator discussions, light propagation direction will be referred to as the c-axis so that there is no confusion between the crystal axis and the propagation axis. (Note: Figs. 3, 4, and 6 use the standard coordinate system for electro-optic crystals, whereas Figs. 1, 2, 8, 9, and 10 use a typical optical coordinate system, with light propagation along the z-axis.) Other cuts and geometries of the crystal may be employed, but in this first example, y-cut is optimal.

Fig. 4 shows a cross section of the electrically controllable de-speckling modulator 160 with a beam of light 320 propagating along the y-axis of the modulator. It may be advantageous for the input and output facets of the modulator to be antireflection coated. Furthermore, since the device effectively perturbs phase fronts, it should be recognized that input light to the modulator can come from a variety of sources simultaneously. The electrically controllable de-speckling modulator 160 may operate on several wavelengths and angular extents simultaneously.

A single modulator site can be defined as the region between top and bottom electrodes 385 and 400. A ray of light, as defined along the x-direction of Fig. 3 propagates along the crystal between top and bottom electrodes 385 and 400. Light passing through that region acquires a phase change $\Delta\phi$ defined as follows:

$$\Delta\phi = (\pi/\lambda) n^3 \gamma_{33} V/d \quad (1)$$

As is seen in Eq. 1, the phase change $\Delta\phi$ is a function of applied voltage V, length of propagation l, distance between electrodes d, wavelength of light λ , refractive index n, and the γ_{33} coefficient for y-cut Lithium tantalate. Given reasonable fabrication parameters such as propagation lengths from 5-50 mm, thickness of 500 μ m, and illumination wavelength in the red spectrum, phase delays of as much as several wavelengths can be generated for operating voltages between 0V and 160V. Understandably, all the input parameters can be altered to render more or less delay along a given channel or modulator site. All delays have been represented by distance or number of waves. It is equivalent to discuss delay as a time delay given by the distance of delay divided by the propagation velocity of the light in the medium.

Referring back to Fig. 3, a plurality of modulator sites 350, 355, 360 is defined by several regions such as the one shown in cross section in Fig. 4. A top electrode 385 and bottom electrode 400 defines each modulator site. It may be useful on fabrication to have a common unpatterned electrode on one side of the device as opposed to patterning both the top and bottom of the device. This allows modulation through differential voltage applied to the electrodes on one

side of the device. The de-speckling modulator is electrically controllable in the sense that the device consists of a series of modulator sites which are addressed by a patterned electrode structure, and which can respond individually or in groups, to pre-determined applied control signals. Each modulator site can be operated independently through means of different applied voltages, different address times, or combinations of both. The electrically controllable de-speckling modulator 160 can be used as either an analog voltage driven modulator, a pulse width modulated device, or a combination of both. The control signals applied to the de-speckling modulator could also be derived from a feedback loop, which monitored the reduction of speckle visibility or contrast, and then adjusted to drive signals to maintain or further reduce speckle magnitude. The width of any given electrode along the x-direction can be anywhere from sub-wavelength in width to literally millimeters in width.

It may be of use to periodically switch the polarities of the top and bottom electrodes, or to introduce a blanking pulse. Such bi-polar operation allows dissipation of space charge in the bulk electro-optic substrate 370. Furthermore, because the operational voltages can be quite high and because the optical field may not be well contained, the electrodes may be patterned with material such as SiO₂ under the electrode to act as a buffer layer 403 (see Fig. 4). Also, an overcoat 410 of acrylic or other insulating material may be applied to prevent arcing in air.

The device structure provided for the electrically controllable electro-optic de-speckling modulator 160 of Figs. 3 and 4 is only one example of this type of de-speckling modulator that could be used in a laser projection display. A second such example is shown in cross section in Fig. 6a, where each modulator site consists of a series of electrodes 420-435 spaced along the y-axis of the crystal. A modulator site can be activated using all or a subset of the electrodes, for instance electrodes 420, 425, and 430, thus providing variable delay even with a single drive voltage. Each electrode (which have distinct lengths) can be driven such that the applied voltage in conjunction with the electrode length can give different known fractions of wavelength delay. For

instance, the first electrode may produce a $1/8$ wavelength delay, the second $1/16$, the third $1/32$, and so forth. The applied voltage can be adjusted such that the same length of electrode renders the same number of wavelengths delay for different wavelengths of light. Additionally the electrodes can be modulated in time individually within each modulator site thus further randomizing the phase.

Another example of an electrically controllable de-speckling modulator useful in a laser projection display, is shown in Fig. 6b. The modulator has added complexity, but greater control as compared to that shown in Fig. 6a. Fig. 6b has different local electrode geometries between adjacent modulator sites. By spacing electrodes 390, 392, 395 within a modulator site (350 for example) and staggering electrodes 390, 397, 399 between adjacent/nearby modulator sites, the modulator is less prone to electrical cross talk effects shown in Fig. 5c.

Similar results can be achieved by allowing space between electrodes both between adjacent modulator sites 350, 353, 360 as well as within a single site 350. On the other hand, as the electrically controllable de-speckling modulator is fundamentally a phase shifter, intended to randomly alter the phase fronts of the incident light in localized areas, the introduction of cross talk between modulator sites can help the intended result by introducing further phase variations. In the event that the designer wishes to contain cross talk effects, the electrodes will need sufficient gaps between them to prevent cross talk. It should be understood that there are other exemplary structures for the electrically controllable de-speckling spatial light modulator, beyond those depicted in Figs. 3, 6a and 6b, which could be conceived of, and which could be used within a laser projection display 100 according to the present invention.

Because the appearance of speckle can be reduced both by spatial variations to the lateral phase profile or by time variations between adjacent regions, the operation of the electrically controllable de-speckling modulator can be modified to accommodate both. In the first case, a lateral electric field distribution is established as a function of address to the electrodes. This distribution, in turn, defines a lateral phase perturbation. In the case of temporal variation, the same field profile may be employed at different sites. However, in

time, the relative fields are varied such that adjacent regions are out of phase with each other. Ideally, a combination of both methods of operation, as shown in Fig. 5d, provides the best result.

An electrically controllable de-speckling modulator 160 can function to distort or scramble the phase fronts of the incident light. Conceptually, this effect is illustrated in Figs. 7a and 7b for the case of collimated light, with planar parallel wave fronts 325 directed at normal incidence onto the modulator 160. As illustrated in Fig. 7a, zero drive voltage is applied to the modulator 160, and the wave fronts 325 emerge unaltered. As illustrated in Fig. 7b, voltages are applied to the modulator sites 350, and distorted wave fronts 330 emerge from the device. Figs. 7c and 7d illustrate the equivalent cases, where an electrically controllable de-speckling modulator 160 is located in convergent space within an optical system. It should be understood that these wave front distortions are exaggerated in extent and only representative of the general concepts. They are not necessarily depictions of wave fronts located 12 apart.

While an electrically controllable de-speckling modulator 160 can distort wavefronts by providing spatial and temporal phase perturbations, the ability of the modulator to affect the appearance of speckle also depends on the design of the system in which it is used. The present invention predominantly considers the case where the electrically controllable de-speckling modulator provides a small delay along a modulator site compared to the coherence length ($\Delta\phi \ll C_L$) of the light source. Indeed, lasers can have coherence lengths ranging from fractions of a mm to several meters in extent (0.1-5.0 mm for Red/Green/Blue optical parametric oscillator type lasers), whereas, the lithium tantalate based de-speckle modulator will only provide a few waves of delay. Thus, as previously stated, this device can be used to cause time variant wave front distortions or aberrations, but not to directly alter the spatial or temporal coherence in an appreciable way. Fortunately, the time and space variable phase can be used to vary or average the speckle within the projected image, thereby reducing the perceptibility of the speckle if the variations are more rapid than the response time of the human eye.

On the other hand, an electrically controllable de-speckling modulator could be used in a system where the provided phase delay is on the same order as the coherence length of the light source ($\Delta\phi \sim C_L$). For example, the typical white light source, such as an arc lamp, emits light with a coherence length C_L and width only several wavelengths in extent, which is comparable to the phase delay from the lithium tantalate based device. Alternately, an electrically controllable de-speckling modulator with about 1.0 mm of delay, could be paired with a small coherence length laser (such as an OPO type laser), to again basically match delay and coherence length ($\Delta\phi \sim C_L$). In such cases, the electrically controllable de-speckling modulator can be used in various ways within the optical system to alter both the spatial and temporal coherence directly. If the controllable phase delay significantly exceeds the coherence length of the light from the light source ($\Delta\phi \gg C_L$), even more dramatic effects can be realized with an electrically controllable de-speckling modulator 160.

The effectiveness of the electrically controllable de-speckling modulator 160 in reducing speckle visibility depends both on the structure and performance of the specific device (Figs. 3, 6a and 6b show such exemplary devices) and the manner in which it is used within laser projection display 100. In particular, an electrically controllable de-speckling modulator 160 may be located prior to the first lenslet array 178a of fly's eye integrator 175 as depicted in Figs. 1 and 2a, or within fly's eye integrator 175 as depicted in Fig. 2b, or similarly after the second lenslet array 178b of fly's eye integrator 175. In the typical fly's eye integrator based optical system used to illuminate a one dimensional device (spatial light modulator 200), the number (N) of lenslets in each lenslet array (178a and 178b) is relatively small, with ~ 6-20 lenslets providing adequate light uniformity. By comparison, the typical spatial light modulator 200, will be an array comprising a relatively high number (M) of tightly packed pixels, with between 256 to 4096 pixels serving most applications. The number (P) of modulator sites in the electrically controllable de-speckling modulator 160 of Figs. 1 and 2 is determined by their effectiveness in reducing speckle visibility,

and is not tightly dependent on either the number (N) of lenslets or the number (M) of modulator pixels.

Assuming that electrically controllable de-speckling modulator 160 is operating under the condition that the phase change or delay it introduces is small relative to the coherence length ($\Delta\phi \ll C_L$) of the laser light beam (a few wavelengths vs. a few mm), then electrically controllable de-speckling modulator 160 can be used to locally alter the wavefronts of the light beams, as in Figs. 7a-4. In this case, there will be many modulator sites per lenslet ($P \gg N$). In order to modify (distort) the wavefronts of imaging beams of lights within the illumination system, electrically controllable de-speckling modulator 160 is used in the far field of the imaged plane (or in one of its conjugate planes). Thus, in the Fig. 1 system, where electrically controllable de-speckling modulator 160 is located prior to the first lenslet array 178a, and where this lenslet array is image conjugate to the spatial light modulator 200, electrically controllable de-speckling modulator 160 is minimally offset from the lenslet array by more than the depth of focus (DOF), and is optimally in the far field of this conjugate plane (approximately $> 10 \cdot \text{DOF}$).

Similarly, as shown in Fig. 2b, if electrically controllable de-speckling modulator 160 is located between first lenslet array 178a and second lenslet array 178b, and in proximity to second lenslet array 178b, then electrically controllable de-speckling modulator 160 is by definition located in the far field of the first lenslet array, and can therefore phase alter the wavefront structure. As the optical system can deliberately be designed to have the light underfill the lenslets of the second lenslet array 178b, the required fill factor for the electrically controllable de-speckling modulator 160 can be reduced, which may permit alternative and less demanding electrode addressing schemes to the modulator sites. Similarly, electrically controllable de-speckling modulator 160 could be located after second lenslet array 178b, and most likely between second lenslet array 178b and condenser lens 185. For these various cases, the wavefront aberrations induced by electrically controllable de-speckling modulator 160 mostly effect the localized interference of wavefronts which contributes to the

creation of speckle. This configuration may also effect the quality of the imaging provided by the beam shaping optics, thereby causing some softness at the edges of the illuminated area.

Alternately, for this same case where the electrically controllable de-speckling modulator 160 provides phase changes or delays which are small relative to the coherence length ($\Delta\phi \ll C_L$) of the laser light, the electrically controllable de-speckling modulator can be positioned within the optical system to act more like a diffuser which scatters or diffracts light, rather than altering the imaging wavefronts within the illumination system. In this case, the number of modulator sites is large compared to the number of lenslets ($P \gg N$), and the electrically controllable de-speckling modulator 160 is located in the near field of the imaging plane within the illumination system. That is, electrically controllable de-speckling modulator 160 is nominally located just before or just after first lenslet array 178a, and should be nominally within the near field ($< 10 \cdot \text{DOF}$) of the conjugate image plane (conjugate to the image plane at spatial light modulator 200).

If, on the other hand, it is assumed that electrically controllable de-speckling modulator 160 is operating under the condition that the phase change or delay it introduces is on the same order as the coherence length ($\Delta\phi \sim C_L$) of the light from the laser source 110, then the device can directly effect the relative temporal coherence of the light for one light beam relative to another. In this case, if the number of modulator sites is identical to the number of lenslets ($P=N$), and the modulator sites are aligned to correspond to a given lenslet of lenslet array 178a, the temporal coherence is altered for the light beam transmitting a given lenslet and modulator site, relative to the others. Each beam will create its own speckle pattern within the illuminated area at spatial light modulator 200, but the ensemble speckle will vary in time as the modulator sites are randomly driven. In this case, electrically controllable de-speckling modulator 160 can be located prior to first lenslet array 178a, but without any strict far field or near field positional restriction. Likewise, electrically controllable de-speckling modulator 160 can be located between the first lenslet array 178a and second lenslet array 178b, or just

after second lenslet array 178b. This configuration would work even better if the phase delay is significantly (2λ - 3λ or more) larger than the coherence length ($\Delta\phi > C_L$).

Alternately, an electrically controllable de-speckling modulator 160, operating under the condition that the phase change or delay it introduces is on the same order as the coherence length ($\Delta\phi \sim C_L$) of the light from the laser source 110, such that the electrically controllable de-speckling modulator can directly effect the relative temporal coherence of the transiting light, can be provided within laser display 100 with a number (P) of modulator sites greater than the number (N) of lenslets ($P > N$). In this case, the electrically controllable de-speckling modulator can be used to randomize the coherence spatially across each lenslet array, and thus across the spatial light modulator 200 and screen 215. In this example, electrically controllable de-speckling modulator 160 is not used to alter the wavefronts with small phase aberrations, but to alter the coherence of one spatial area relative to another, and effectively synthesize a nearly incoherent source. If the number of modulator sites is modestly greater than the number of lenslets ($P = 8 \times N$ for example), the electrically controllable de-speckling modulator 160 can be located prior to first lenslet array 178a, but without any strict far field or near field positional restriction (as long as the modulator sites are not small enough to diffract, scatter, or diffuse appreciable light). In this case, the beam of light passing through each lenslet is split into relatively large adjacent regions, with the temporal coherence varying amongst the regions. However, if there are many modulator sites relative to the number of lenslets ($P \gg N$), such that the electrically controllable de-speckling modulator 160 functions more like a diffuser, then de-speckling modulator 160 should be located in the near field of first lenslet array 178a. In that case, electrically controllable de-speckling modulator 160 may be located just before or just after lenslet array 178a, and should be nominally within the near field ($< 10^\circ$ DOF) of the conjugate image plane (conjugate to the image plane at spatial light modulator 200). These configurations would work even better if the phase delays provided by de-speckle

modulator 160 are significantly (2λ - 3λ or more) larger than the coherence length ($\Delta\phi > C_L$).

In summary, laser display system 100 is designed to provide a projected image on a distant screen 215 that is free from perceptible speckle, by using a combination of speckle reduction/de-correlation techniques. The use of diffuser 150 not only re-defines the effective lagrange or etendue of the light, but also breaks the coherent incident beam into a multitude of smaller, less spatially coherent wavefronts. Thus use of a light integrating system, such as fly's eye integrator 175, which divides the light into beamlets which are reimaged to create a uniform area of illumination, also provides further speckle reduction by overlapping the many local contributions from the diffuser across the screen. Finally, the use of electrically controllable de-speckling modulator 160 provides means to disrupt the local phase of portions of the illuminating light, relative to other portions of the illuminating light, thereby altering the local spatial and/or temporal coherence relationships. This allows either the local wavefront phase structures, the temporal coherence relationships between wavefronts, or the temporal coherence across spatial areas to be altered. Furthermore, it should be noted that speckle reduction in laser display 100 could have diffuser 150 attached to a motion mechanism, which imparts a linear, rotary, or random motion to the diffuser, such that the diffuser 150 moves by at least the characteristic feature size of the diffusing surface. The frequency of the motion must be faster than the flicker frequency (> 40 Hz). Speckle visibility is then further reduced by decorrelating the speckle pattern by time averaging the position and magnitude of the speckle in local areas across the full spatial extent of the image.

Depending on its construction and operation, the electrically controllable de-speckling modulator 160 may impart sufficient phase perturbations, such as diffraction or scatter, to the light beam to actually cause the source lagrange or etendue to be measurably increased. In the case of projection systems designed with a linear spatial light modulator 200 requiring a relatively coherent illumination in the array direction, a small change in source lagrange provided by the electrically controllable de-speckling modulator 160 may be

sufficient to meet the imaging requirements of the projection system. In that case, the laser display system 100 may be constructed without a diffuser 150.

It also should be understood that the cross array optics in Figs. 1 and 2a show a simplified optical system with just one cylindrical lens, cross array condenser 195. Cross array condenser 195 conditions the light beam in the cross array direction, to optimize it for interaction with linear spatial light modulator 200. It should be understood that multiple cylindrical lens elements could be used for this beam conditioning. It should also be understood that some of the lens elements within laser projection system 100 prior to linear spatial light modulator 200 could be spherical, and shape both the array and cross array beams. Likewise, projection lens 205 could also include cylindrical lenses (not shown), to provide further control of either the array direction or cross array direction spot formation at the screen 215. Similarly, it should be understood that cross array optics (not shown) could be provided prior to electrically controllable de-speckling modulator 160 to pre-condition the light beam so as to optimize the interaction of the light through the electrically controllable de-speckling modulator. In that case, cross array condenser 195 or equivalent would adapt the cross array light beam exiting electrically controllable de-speckling modulator 160 to optimize it for input to linear spatial light modulator 200. It should also be understood that alternate beam homogenizing optics to the fly's eye integrator could be used. In particular, an integrating bar/kaleidoscope, much as described in (Moulin patent), could be used within an alternate design for the beam shaping optics 170, and provide both uniform illumination, as well as a contributory effect to speckle reduction in cooperation with diffuser 150 and electrically controllable de-speckling modulator 160.

An alternate construction for laser projection display 100 is shown in Fig. 8, in which a beamsplitter array 240 is used to provide optical path delay differences so as to reduce the coherence of the composite laser beam 250.

Beamsplitter array 240 comprises an arrangement of (R) partially reflecting mirrors, which create a series of beamlets 245 with optical path length differences (Δd) between adjacent beamlets 245 that are on the order of the coherence length

of the laser or laser. Optimally the optical path differences (Δd) are on the same order of size as the coherence length C_L of the laser 110. The mirrors of beamsplitter array 240 would be partially transmitting, and partially reflecting, with the reflectivity increasing progressively from the first mirror (241a) to the last mirror (241e). Although beamsplitter array 240 is illustrated as an array of mirrors, prism arrays and other structures could be used. Beamsplitter array 240 effectively works as a beam expander, using the R beamlets to create a composite laser beam 250. However, as the R beamlets travel different optical path lengths ($\Delta d_1, \Delta d_2, \Delta d_3$, etc...) which are comparable to the coherence length C_L , the temporal coherence of the light will vary across the spatial extent of composite laser beam 250. Ideally, each of the R beamlets 245 are temporally incoherent relative to the others. However, the scheme is still useful even if the temporal coherence changes more slowly, such that groups of beamlets 245 are coherent to each other, as these groupings will tend to change randomly in time, as the coherent emissive state of the laser 110 fluctuates in time.

As the typical laser beam 115 has a non-uniform light intensity profile (a Gaussian profile being common), each of the beamlets 245 will also be non-uniform, and composite laser beam 250 will be non-uniform as well. As with the Fig. 1 system, diffuser 150 is inserted to change the effective source lagrange or etendue to match the imaging requirements. Diffuser 150 also helps to make composite laser beam 250 somewhat more uniform and less coherent. Again as previously, a fly's eye integrator 175 is used to both improve the illumination uniformity and reduce speckle visibility at spatial light modulator 200. However, in this case, first lenslet array 178a is designed to have each beamlet 245 illuminate M lenslets, so that each beamlet 245 is transformed into uniform illumination at the light valve. Thus there are a total of at least $M \times R$ lenslets in each lenslet array 178a and 178b. The effect at the screen 215 is that each of the R laser beams will produce their own fine speckle pattern dictated by the diffuser, the M fly's eye lenslet pairs used by a given beam, and the screen. The $M \times R$ speckle patterns will add incoherently to produce an overall averaging even without the use of electrically controllable de-speckling modulator 160 or the

motion of diffuser 150. Although in some less critical applications, this degree of speckle reduction may be sufficient, for critical applications, laser display system 100 of Fig. 8 is further improved with the addition of electrically controllable de-speckling modulator 160. As the temporal coherence within composite laser beam 250 is already significantly variable, electrically controllable de-speckling modulator 160 can be used to alter the phase wavefronts within the beamlets 245, assuming the applied phase change is small relative to the coherence length ($\Delta\phi \ll C_L$). As with the prior discussion, electrically controllable de-speckling modulator 160 can be positioned (see Fig. 8) within laser display 100 in advance of first lenslet array 178a, such that it is in the far field (well outside the depth of focus (DOF)) of the conjugate image plane of beam shaping optics 170. Similarly, as previously, electrically controllable de-speckling modulator 160 can be located in the downstream far field of the conjugate image plane, in proximity to second lenslet array 178b, either before as in Fig. 2b, or after. Alternatively, if electrically controllable de-speckling modulator 160 provides phase changes comparable to the coherence length ($\Delta\phi \sim C_L$), this modulator can be used to vary the temporal and spatial coherence across regions within each of the M lenslets, where these regions are relatively large compared to the wavelength of light (to neither scatter nor diffuse).

Thus far, this invention for a laser display system utilizing both an electrically controllable de-speckling modulator and a spatial light modulator for imparting image data, has been described with respect to the use of one dimensional light modulators. There are a wide variety of two dimensional (area) spatial light modulators which can be used in electronic projection systems, with liquid crystal light valves (LCDs) and micro-mechanical mirror arrays (including the digital mirror devices (DMDs) from Texas Instruments) being the most prominent. Relative to the laser display system of Fig. 1, the primary impact of switching from a one dimensional spatial light modulator to a two dimensional type, is that both the illumination optics and the electrically controllable de-speckling modulator 160 must be modified to work two dimensionally. In that case, the fly's eye integrator 175 typically use fly's eye lenslet arrays 178 (a,b)

laid out in a two dimensional pattern, where the lenslets have spherical surfaces. Likewise, diffuser 150 provides controlled two dimensional (or spherical) diffusion, rather than the one-dimensional diffusion preferred in the Fig. 1 linear system. Such diffusers are available as holographic diffusers from Physical Optics Corp. or a randomized microlens array from Corning - Rochester Photonics Corp.

The various examples of spatial light electrically controllable de-speckling modulator 160 detailed in Figs. 3, 4, 6a and 6b are one dimensional or linear devices. It is possible to construct a two dimensional electrically controllable de-speckling modulator by stacking a series of these devices, or by placing a series of these devices in offset locations within the optical system. It should also be understood that other types of electrically controllable de-speckling modulators can be designed, which use other electro-optical materials more conducive to use as a two dimensional structure, which could then be placed in a laser display system with a two dimensional image modulating spatial light modulator array.

For example, Fig. 9 shows a cross sectional view of a laser projection display 100 using an area type modulator array, such as an LCD. As before, laser 110 emits a laser beam 115 which is pre-conditioned by beam expansion optics 120, diffuser 150, and beam shaping optics 170 to illuminate a spatial light modulator (liquid crystal display 255). And as previously, diffuser 150, fly's eye integrator 175, and electrically controllable de-speckling modulator 160 all contribute to reduce the presence of speckle across two dimensions at the spatial light modulator and at the screen 215. Unlike the system of Fig. 1, in the system of Fig. 9, a two dimensional on screen image is not formed by scanning, but by using projection lens 205 to directly image the spatial light modulator (liquid crystal display 255) to the screen 215. The illumination light passes through a pre-polarizer 260, and a polarization beam splitter 265. Liquid crystal display 255 modulates the illuminating light, rotating the polarization state of this light on a pixel by pixel basis, according to the applied command signals. Modulated image bearing light beam 275, which is directed to the screen 215 by

projection lens 205, is turned by polarization rotated light which reflects off polarization beam splitter 265. Nominally polarization analyzer 270 is used in a crossed orientation, to define the dark state. As the typical laser source emits polarized light, it may not be necessary to utilize pre-polarizer 260 in the laser display 100 of Fig. 9. In this case, it would be necessary that laser beam 115, as emitted by laser 110, be sufficiently polarized (100:1 for example), and that neither diffuser 150 or electrically controllable de-speckling modulator 160 significantly degrade this innate polarization contrast.

Similarly, Fig. 10 shows a cross-sectional view of a laser projection display using a micro-mechanical mirror array 280, such as the DLP chip available from Texas Instruments. Unlike systems using a liquid-crystal spatial light modulator, which rely on controlled polarization effects to modulate the light, the micro-mechanical mirror array 280 utilizes angular control of the beamlets of light on a pixel-by-pixel basis. This system is substantially the same as the system shown in Fig. 1, except the illumination converges to an aperture 290 beyond the micro-mechanical mirror light array 280. Individual pixels are formed by micromirrors that either direct light through the aperture 290 of the projection lens 205, or toward a stop 285 (i.e. a Schlieren optical system). Pixel brightness is controlled by selecting the proportion of time within a frame that light is directed through the lens aperture 290. This type of system can be constructed either with a two dimensional spatial light modulator array, a 2D fly's eye system, and a 2D electrically controllable de-speckling modulator 160 as in Fig. 10, or alternately with a 1D spatial light modulator array, a 1D fly's eye system, a 1D electrically controllable de-speckling modulator 160, and a scanner, such as the galvanometer used in Fig. 1.

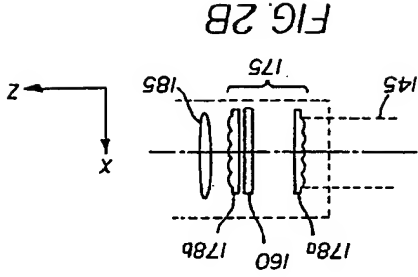
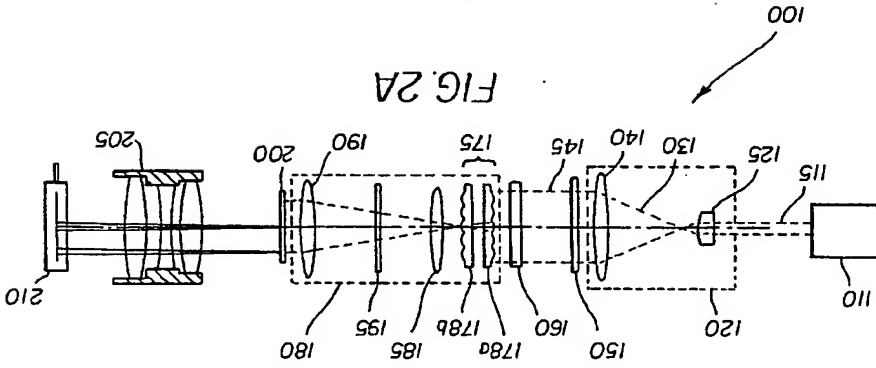
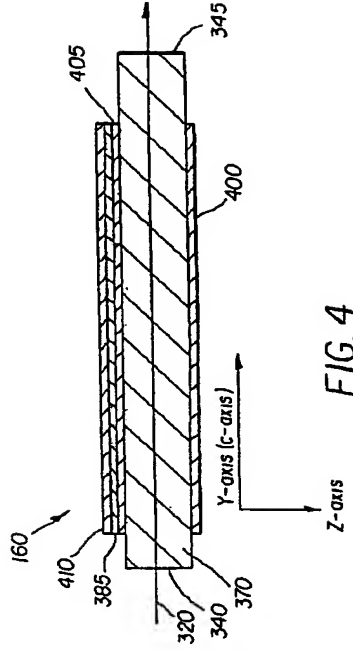
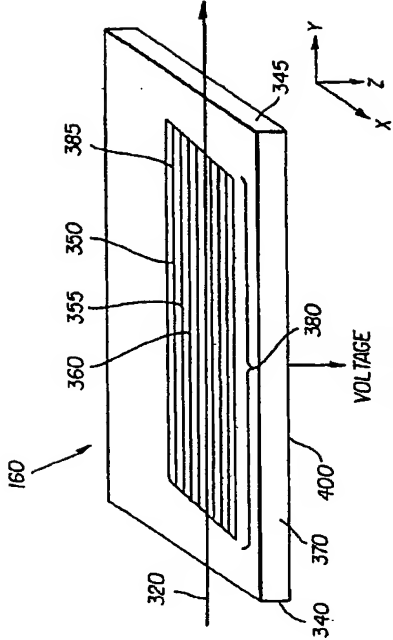
For simplicity, the invention has been demonstrated with a single laser beam and single spatial light modulator, although the broader discussion has been directed towards a full color RGB projection display. It should be understood that a system can be constructed with separate red, green, and blue light beams which follow separate optical paths to illuminate the respective red, green, and blue spatial light modulators. The modulated light beams would be

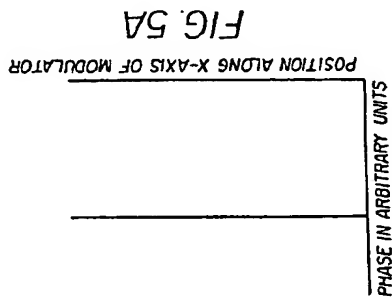
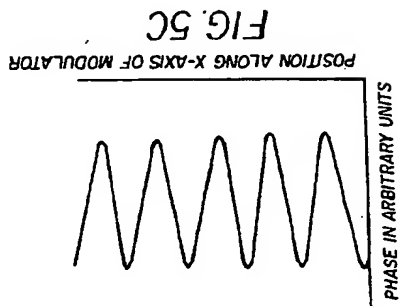
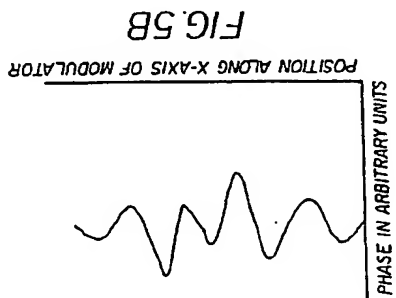
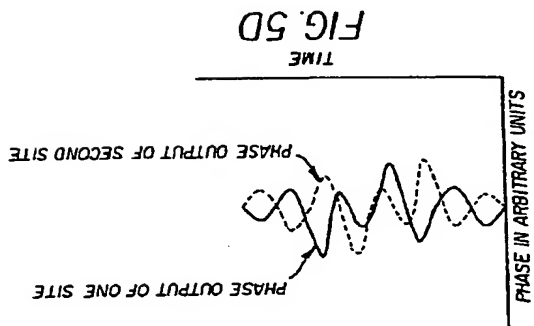
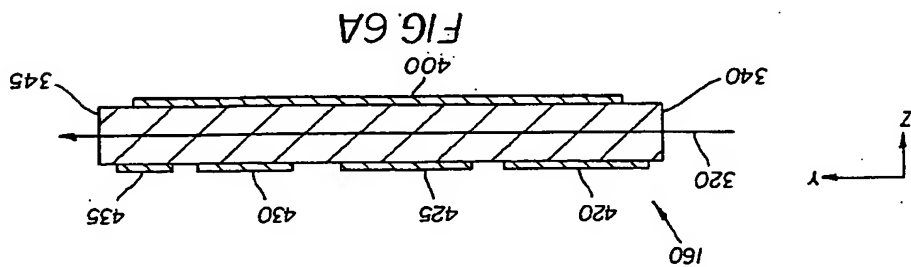
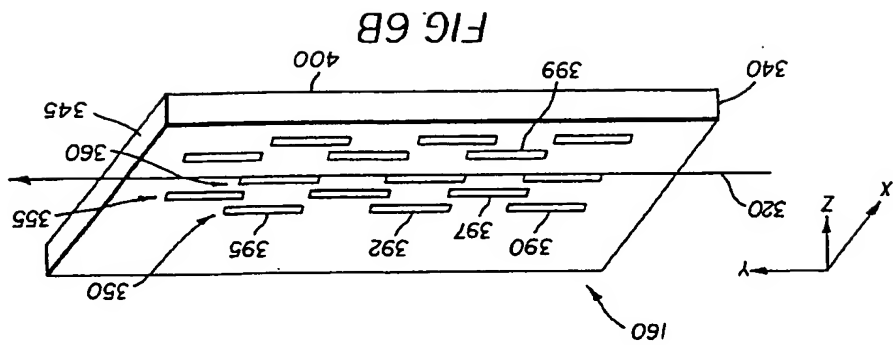
color combined, typically by an x-prism located before the projection lens, and the resulting light beam would be imaged to the screen to provide a polychromatic image. The separate red, green, and blue beams can originate from three separate lasers, from one OPO type laser package using a combination of non-linear optics to output three beams, or from an OPO type laser package integrated to provide a single white light laser beam output, which is subsequently color split.

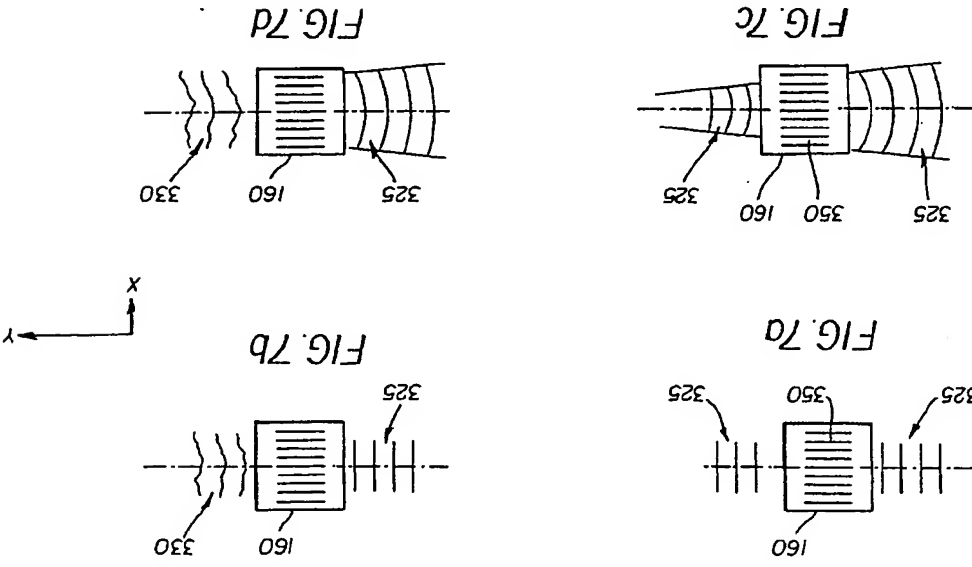
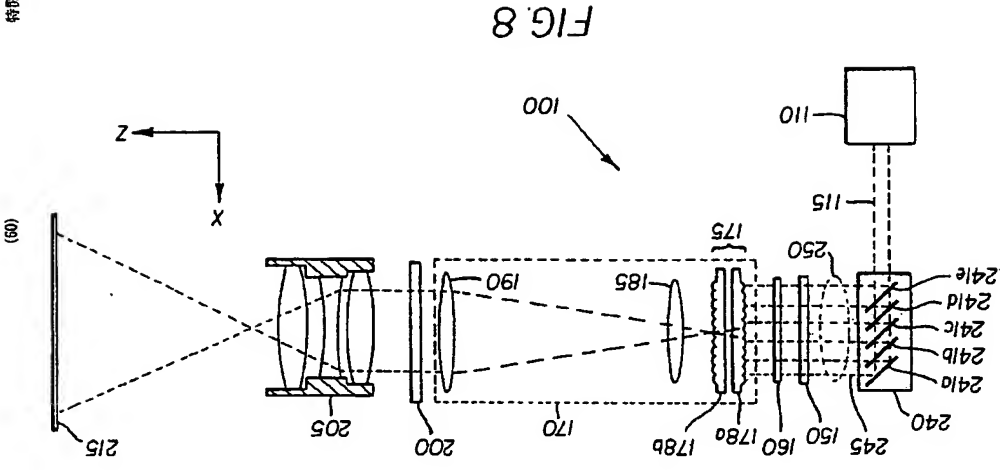
PARTS LIST

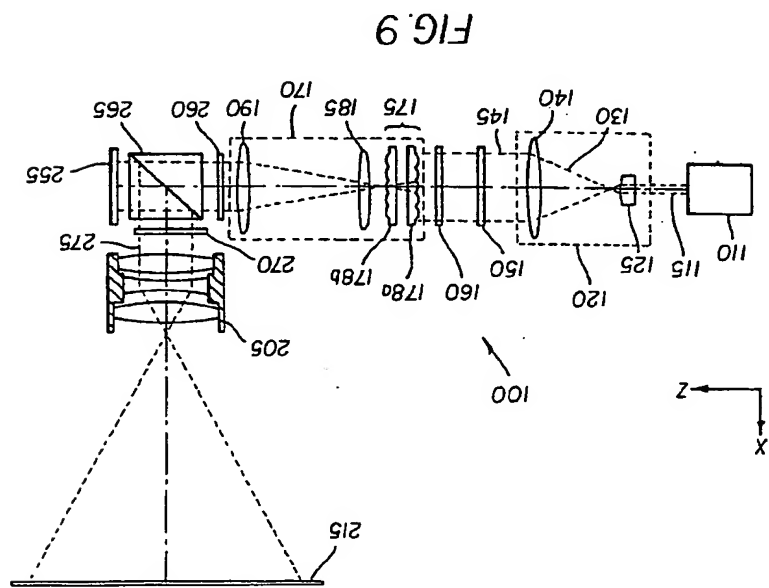
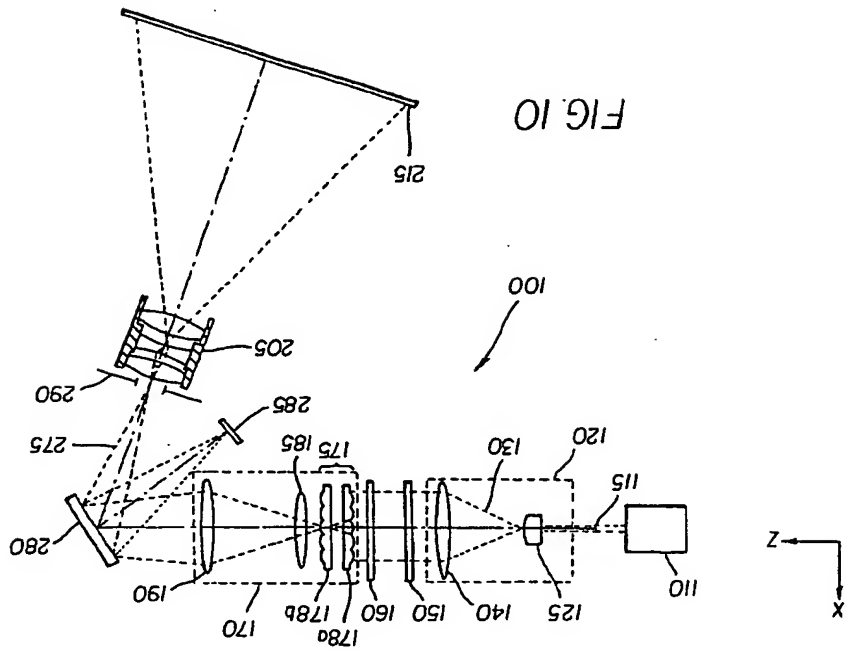
100	laser display system
110	laser
115	laser beam
120	beam expansion optics
125	diverging lens
130	diverging beam
140	collimating lens
145	collimated beam
150	diffuser
160	electrically controllable de-speckling modulator
175	fly's eye integrator
178a	first lenslet array
178b	second lenslet array
180	beam shaping optics
185	condenser lens
190	field lens
195	cross array condenser
200	linear spatial light modulator
205	projection lens
210	galvanometer mirror
215	screen
220	line image
225	area image
240	beam splitter array
241(a-c)	mirrors
245	beamlets
250	composite laser beam
255	liquid crystal display
260	pre-polarizer

265	polarization beam splitter
270	polarization analyzer
275	modulated image bearing light beam
280	micro-mechanical mirror array
285	stop
290	aperture
320	light
325	wave front
330	distorted wave front
340	input facet
345	output facet
350	modulator site
355	modulator site
360	modulator site
370	bulk material or substrate
380	delay region
385	top electrode
390	electrode
392	electrode
395	electrode
397	electrode
399	electrode
400	bottom electrode
405	buffer layer
410	overcoat
420	electrode
425	electrode
430	electrode
435	electrode









ABSTRACT OF THE DISCLOSURE

A display apparatus includes a laser light source for emitting a light beam having a coherence length; a beam expander for expanding the light beam; a spatial light modulator; beam shaping optics for shaping the expanded laser beam to provide uniform illumination of the spatial light modulator, the beam shaping optics including a fly's eye integrator having an array of lenslets; a diffuser located in the light beam between the laser light source and the beam shaping optics; an electrically controllable de-speckling modulator for modifying the temporal and spatial phase of the light beam; and a projection lens for producing an image of the spatial light modulator on a distant screen.